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(54) **ALIGNMENT METHODS IN FLUID-FILLED MEMS DISPLAYS**

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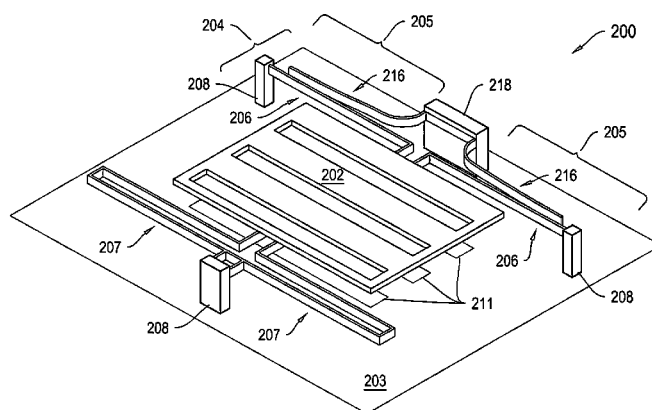
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(57) **ABSTRACT**

This invention relates to MEMS display apparatus and methods for assembly thereof that include a plurality of light modulators having components substantially surrounded in a liquid that reduces the effects of stiction and improves the optical and electromechanical performance of the display apparatus. The invention also relates to methods for aligning components of a MEMS display to establish a correspondence between the plurality of light modulators and a plurality of apertures to regulate the transmission of light through the apparatus.

**31 Claims, 29 Drawing Sheets**



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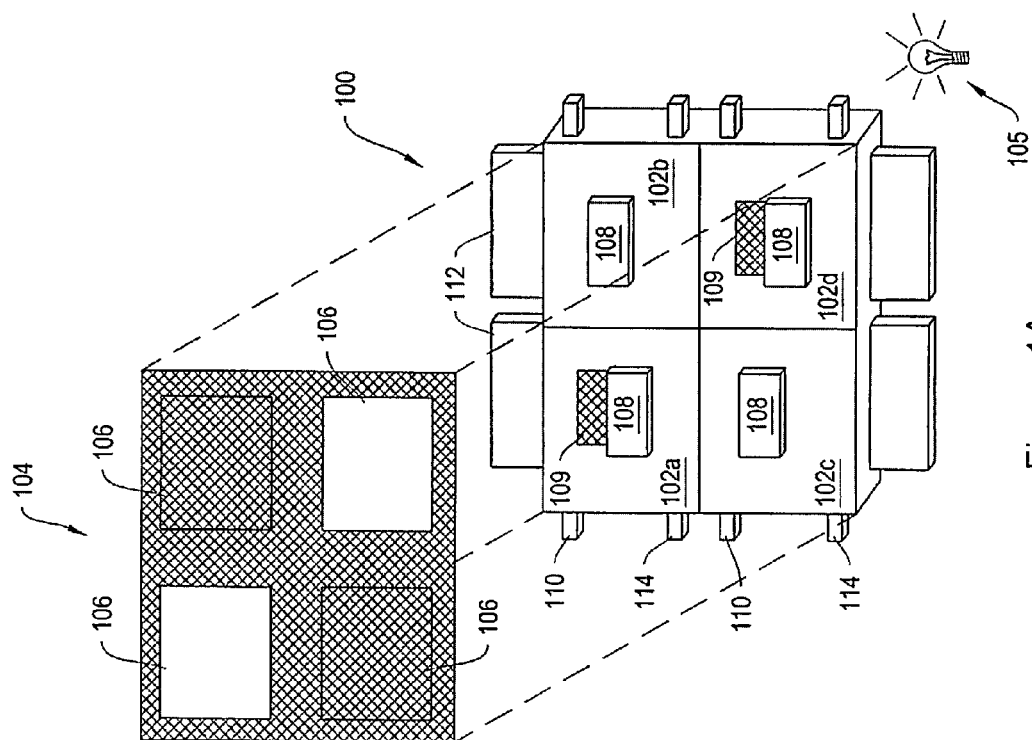


Figure 1A

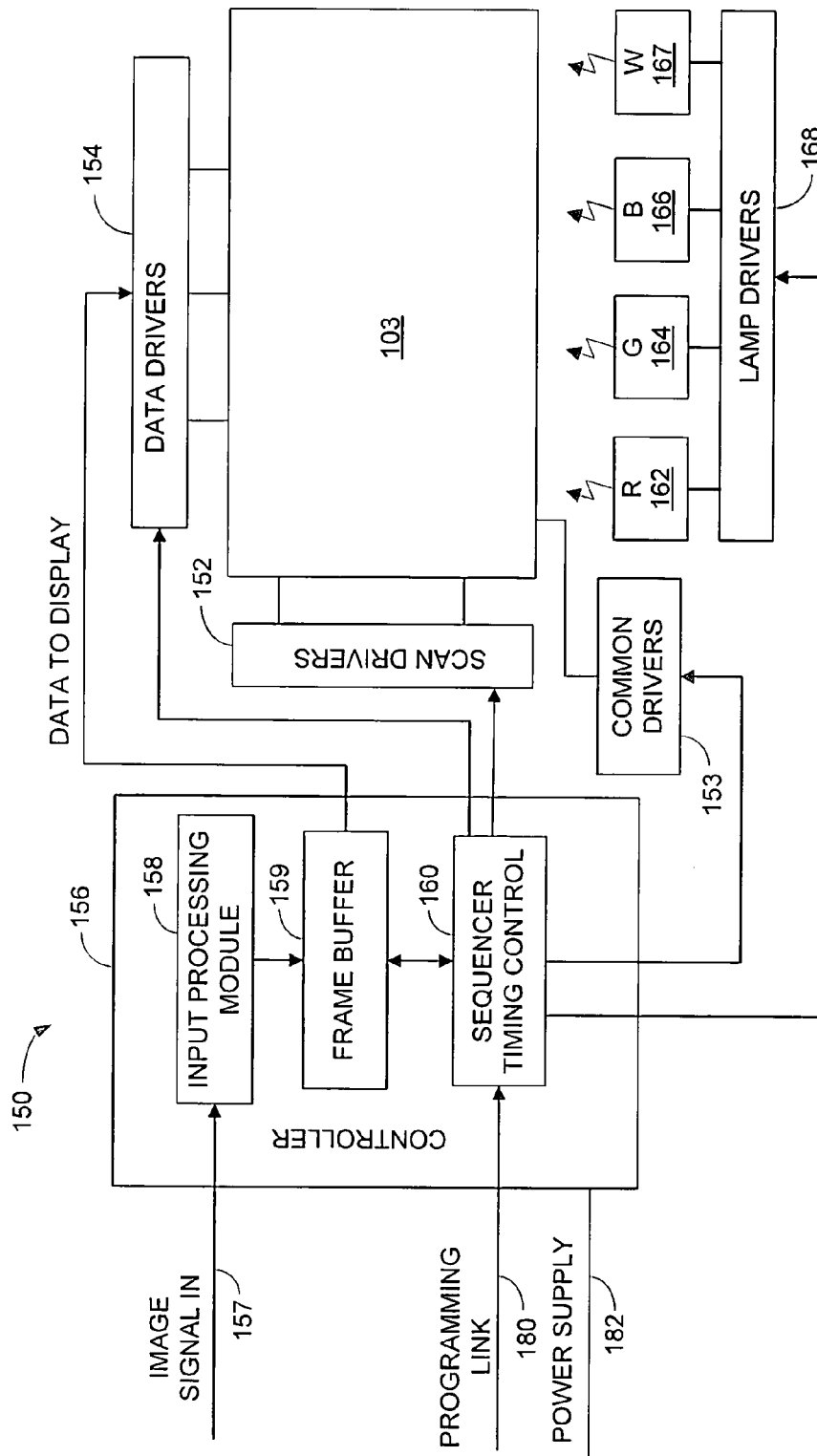


Fig. 1B

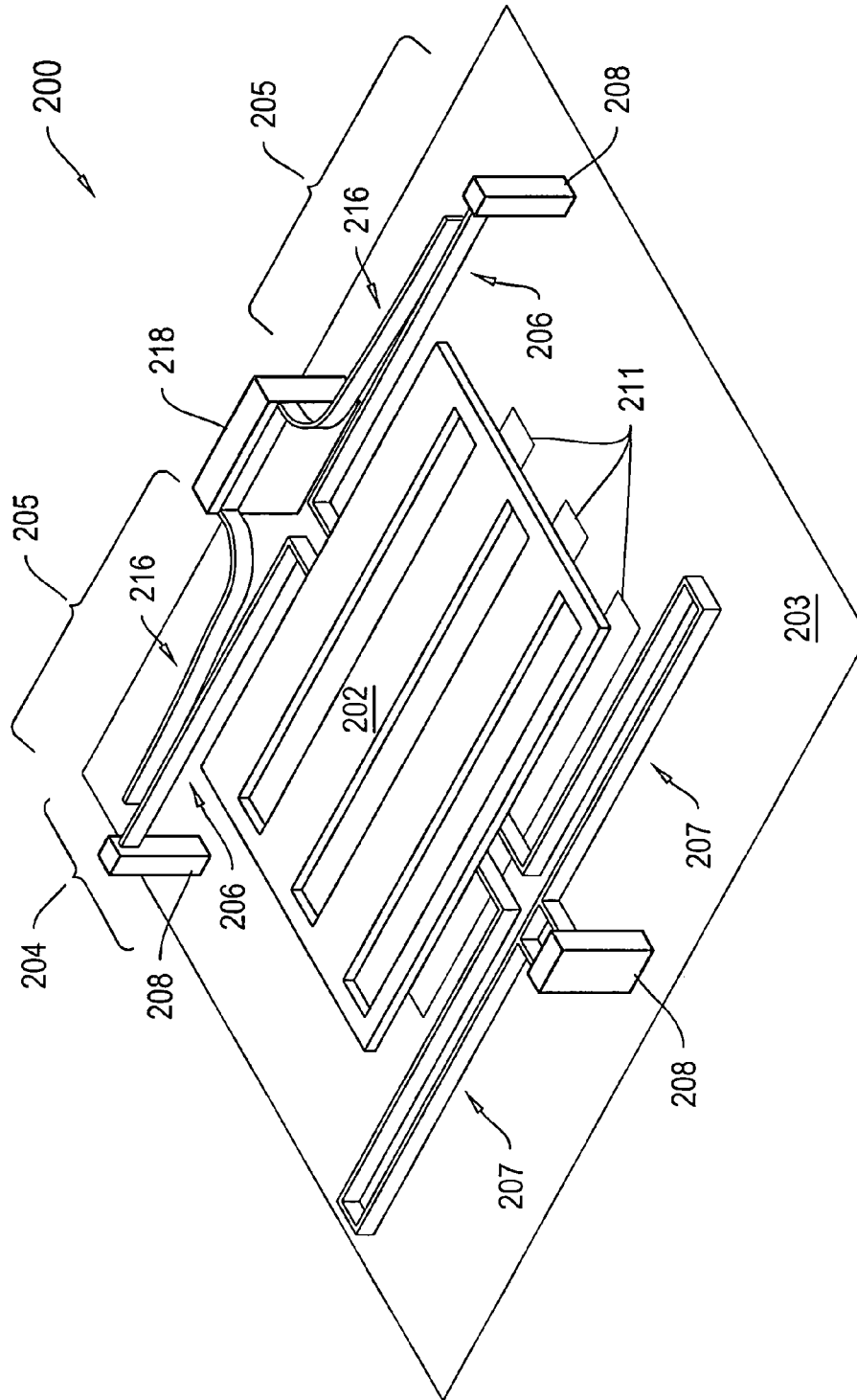


Figure 2A

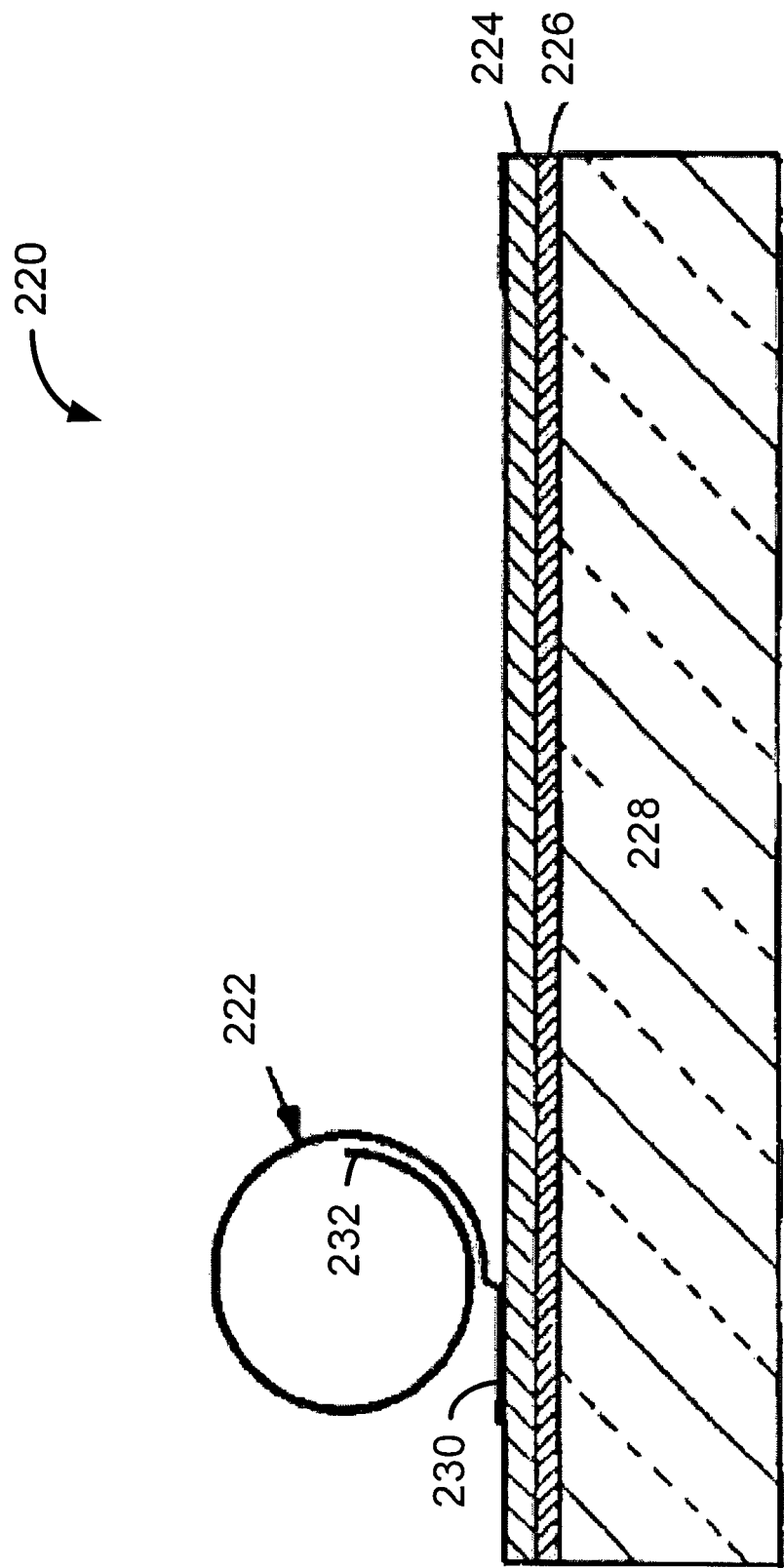


Figure 2B

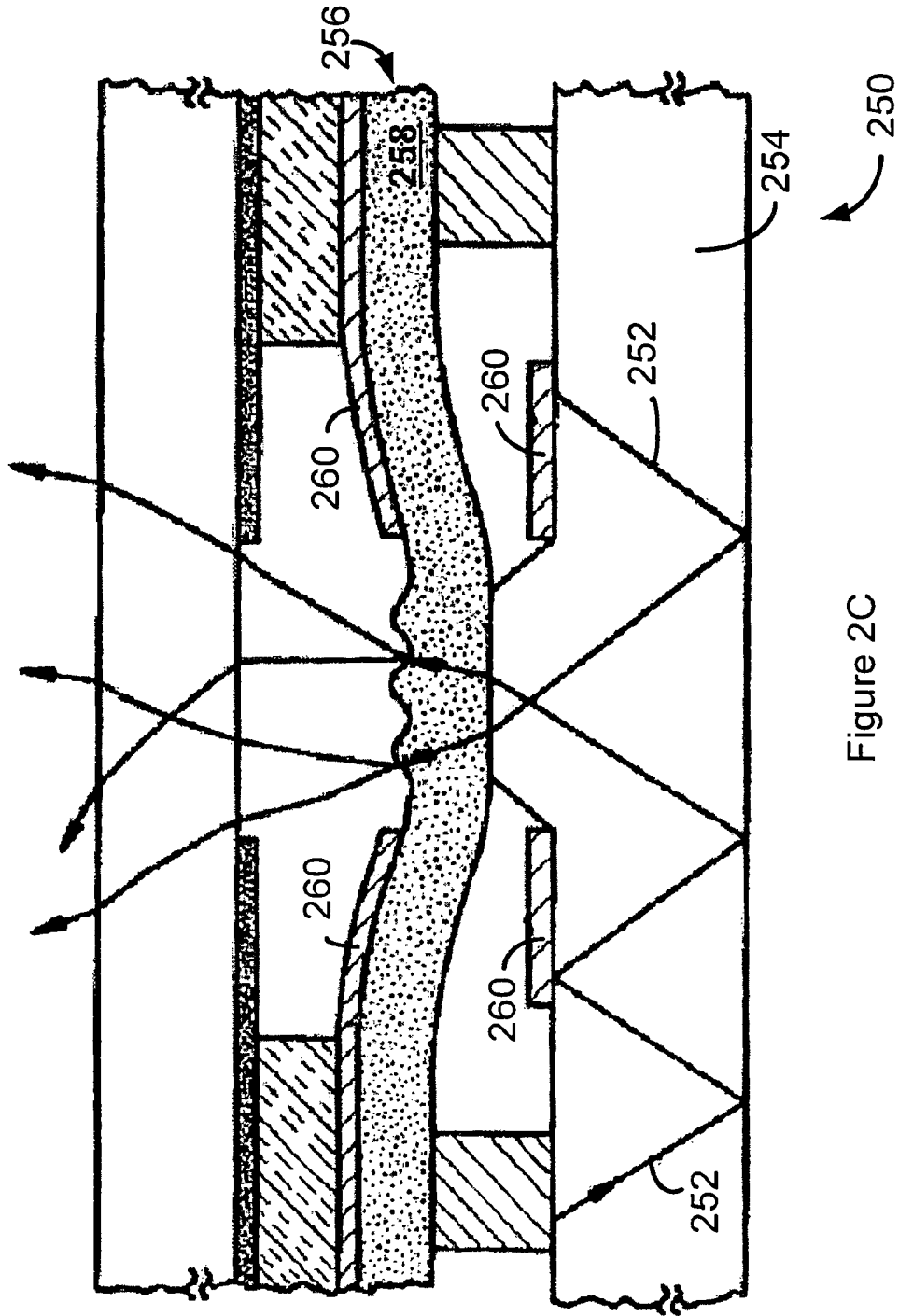


Figure 2C



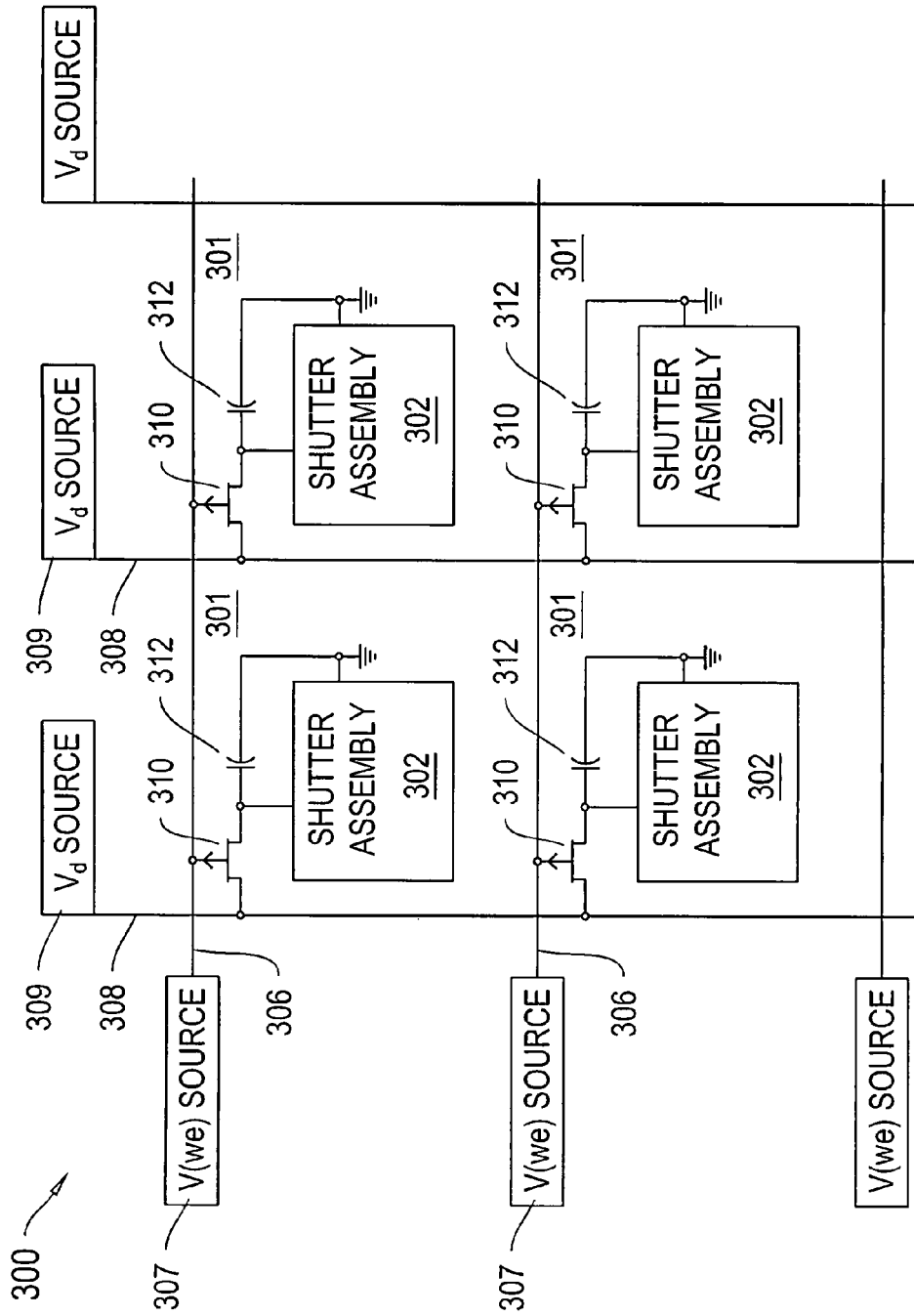


Figure 3

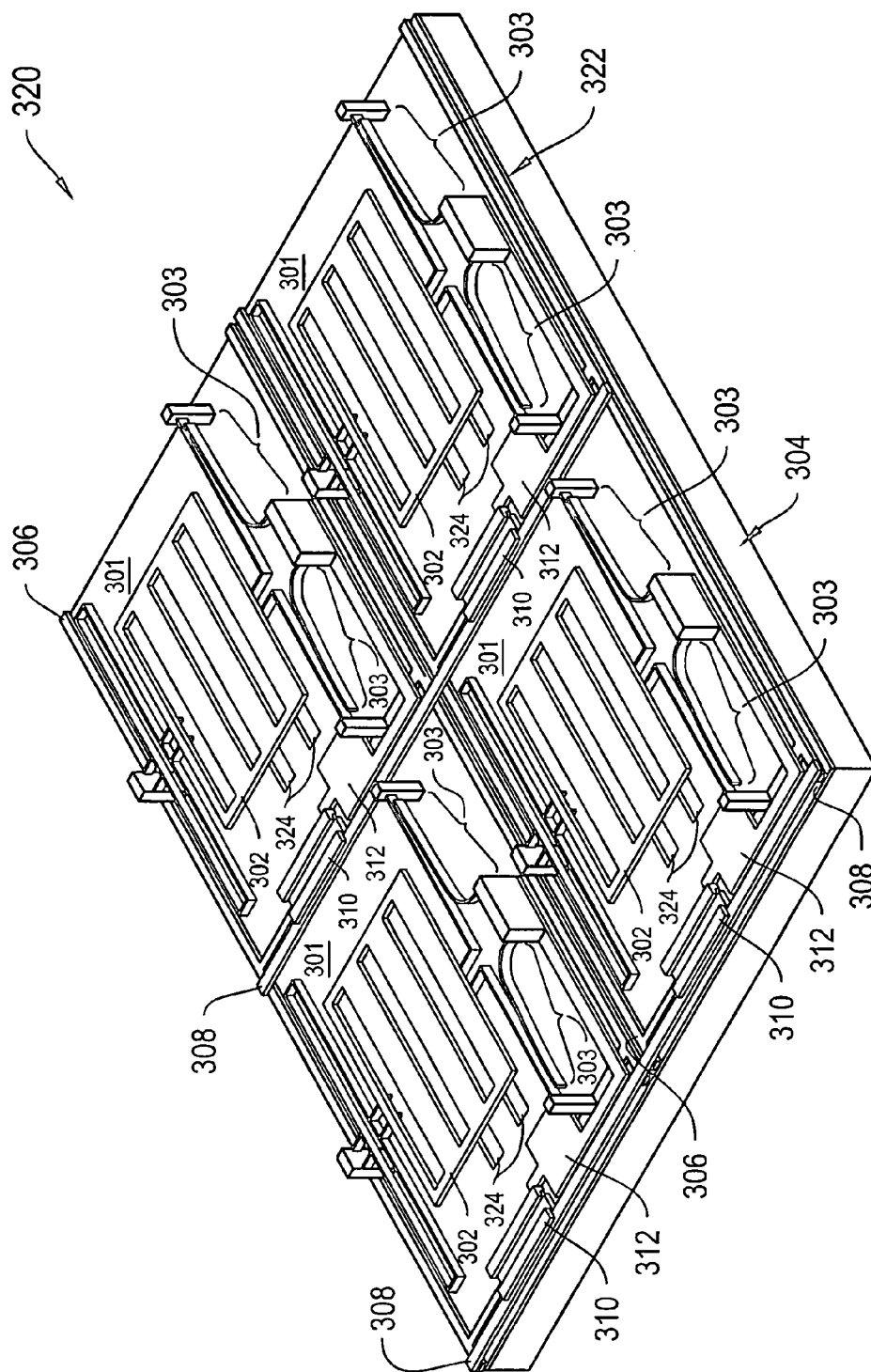


Figure 4

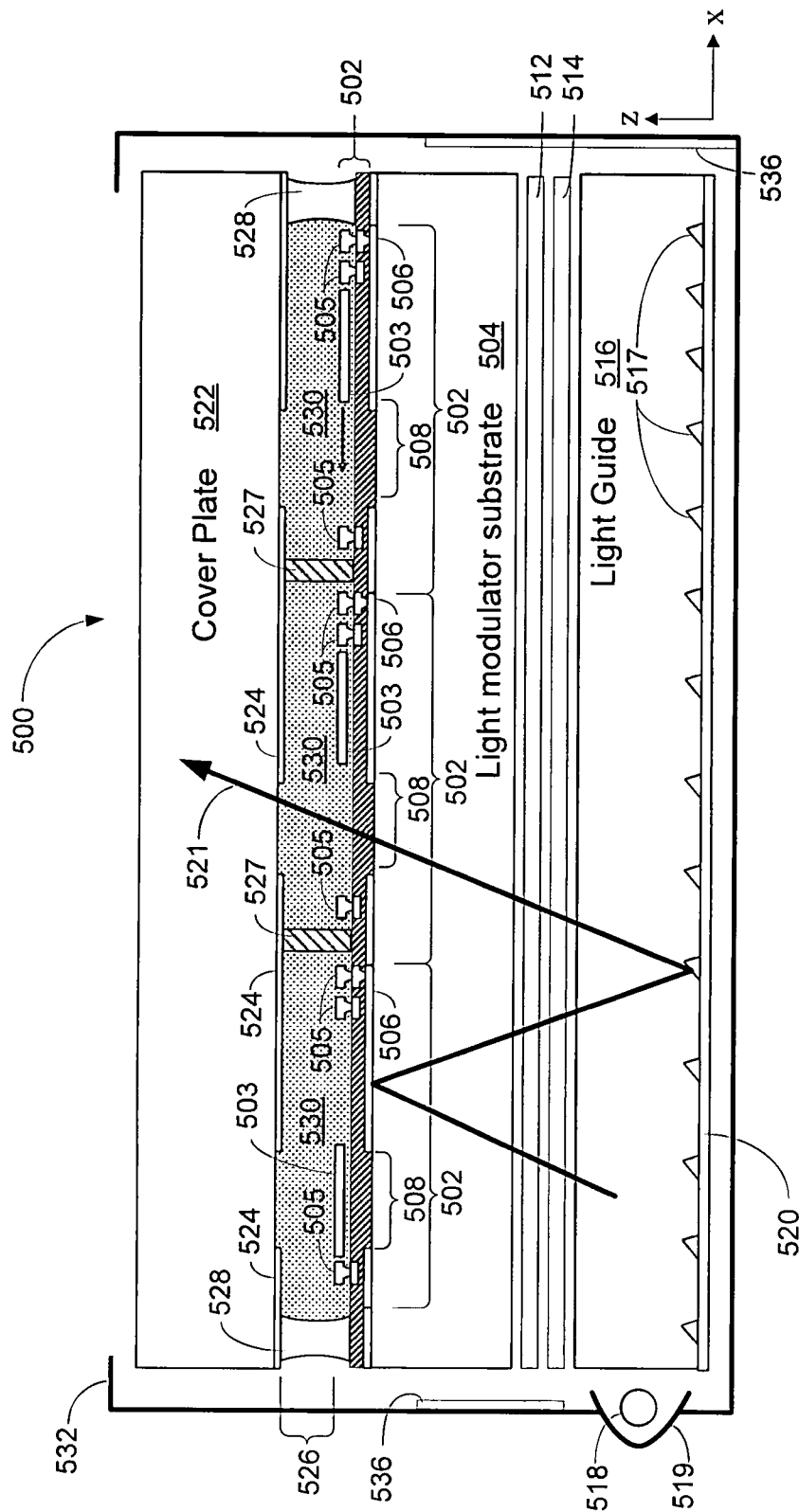


Fig. 5

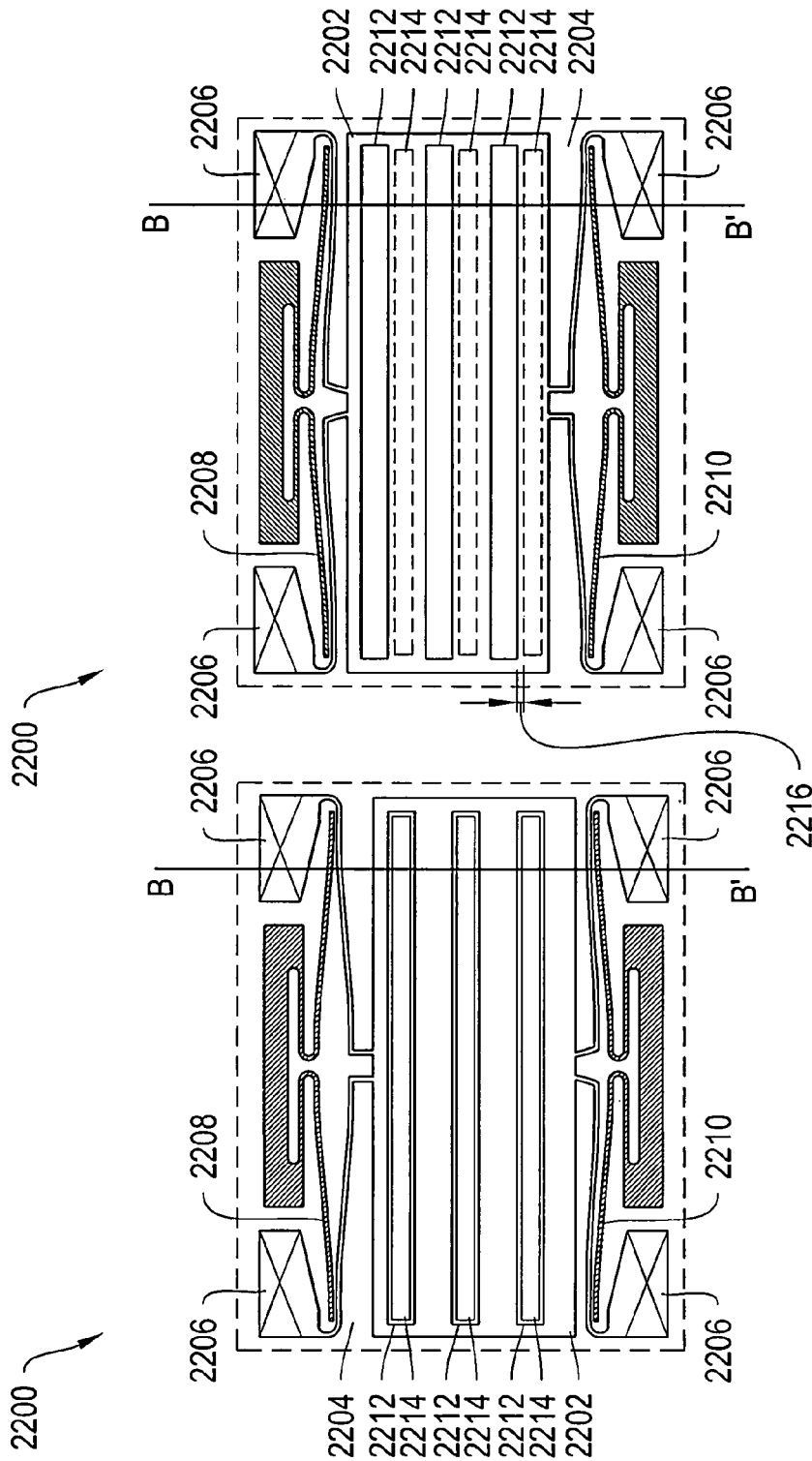


Figure 6B

Figure 6A

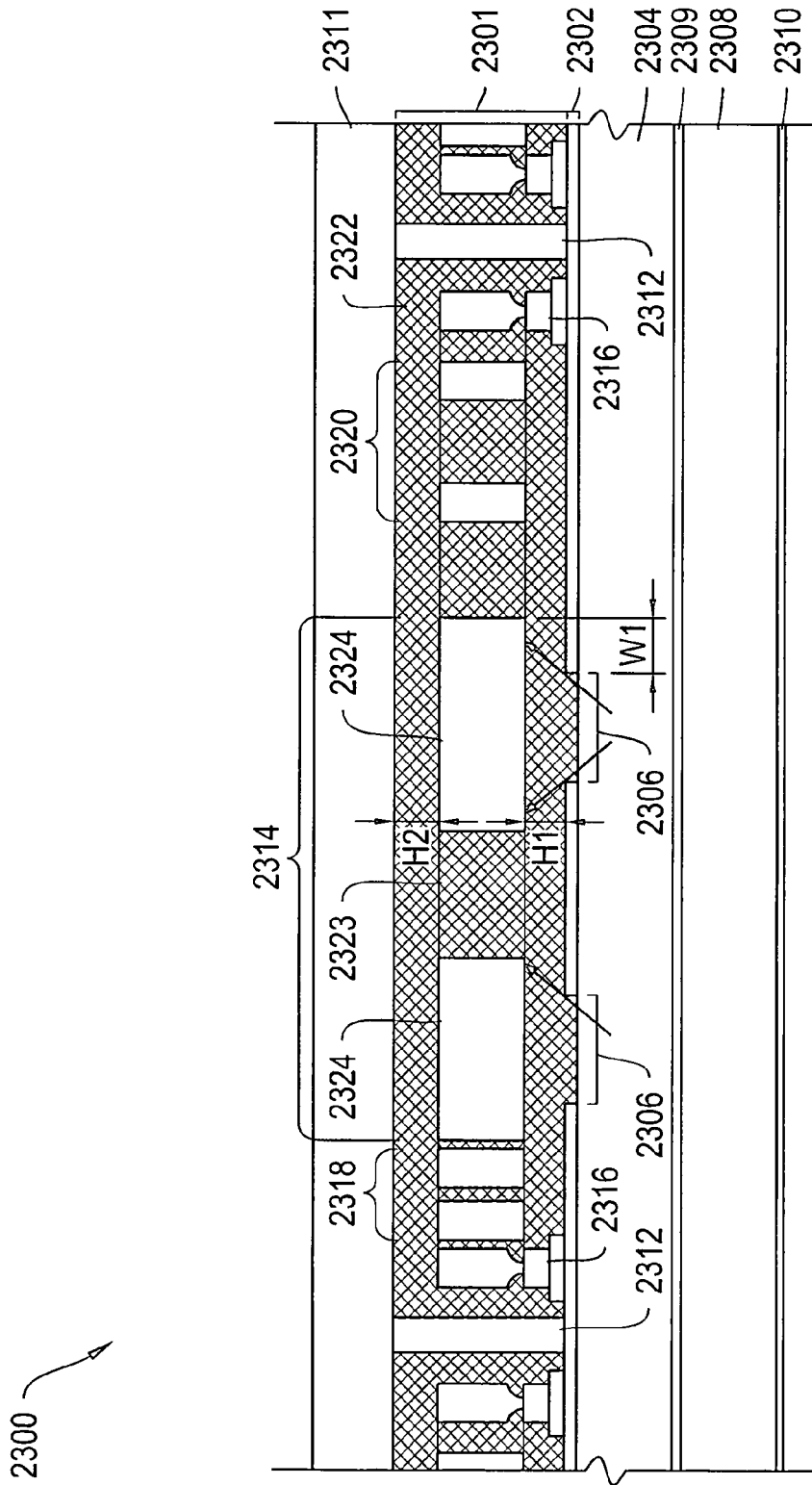


Figure 7A

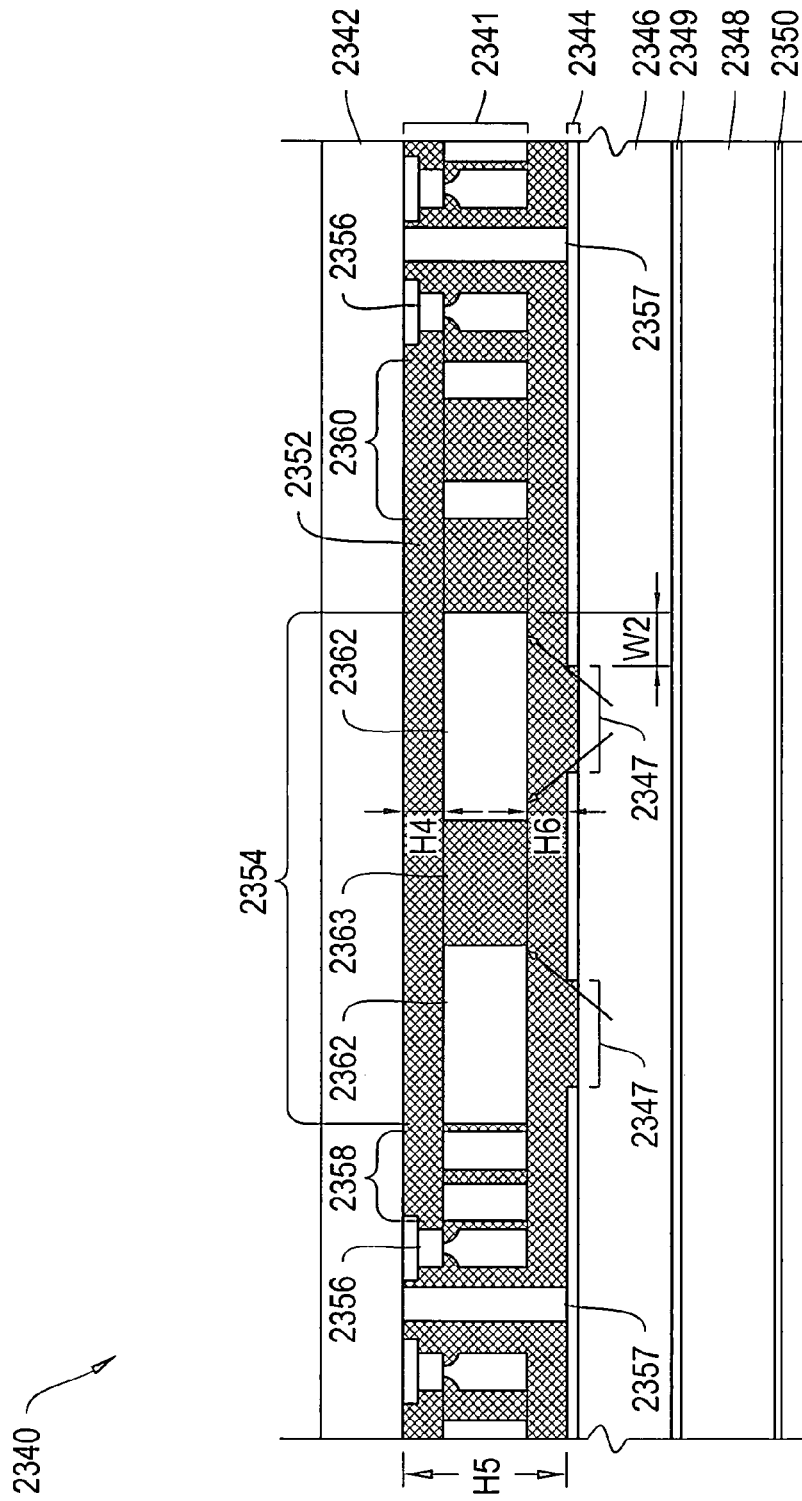


Figure 7B

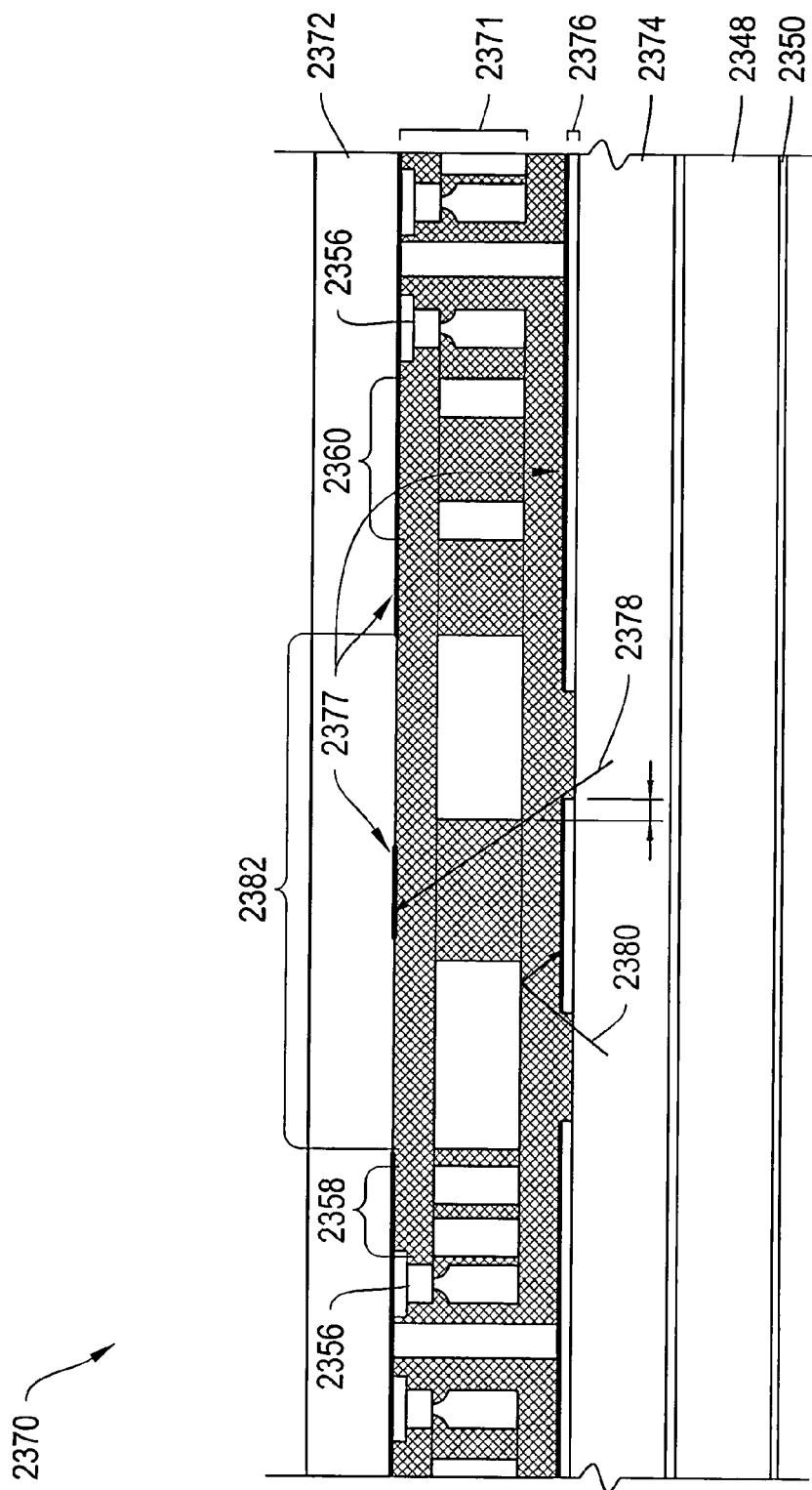


Figure 7C

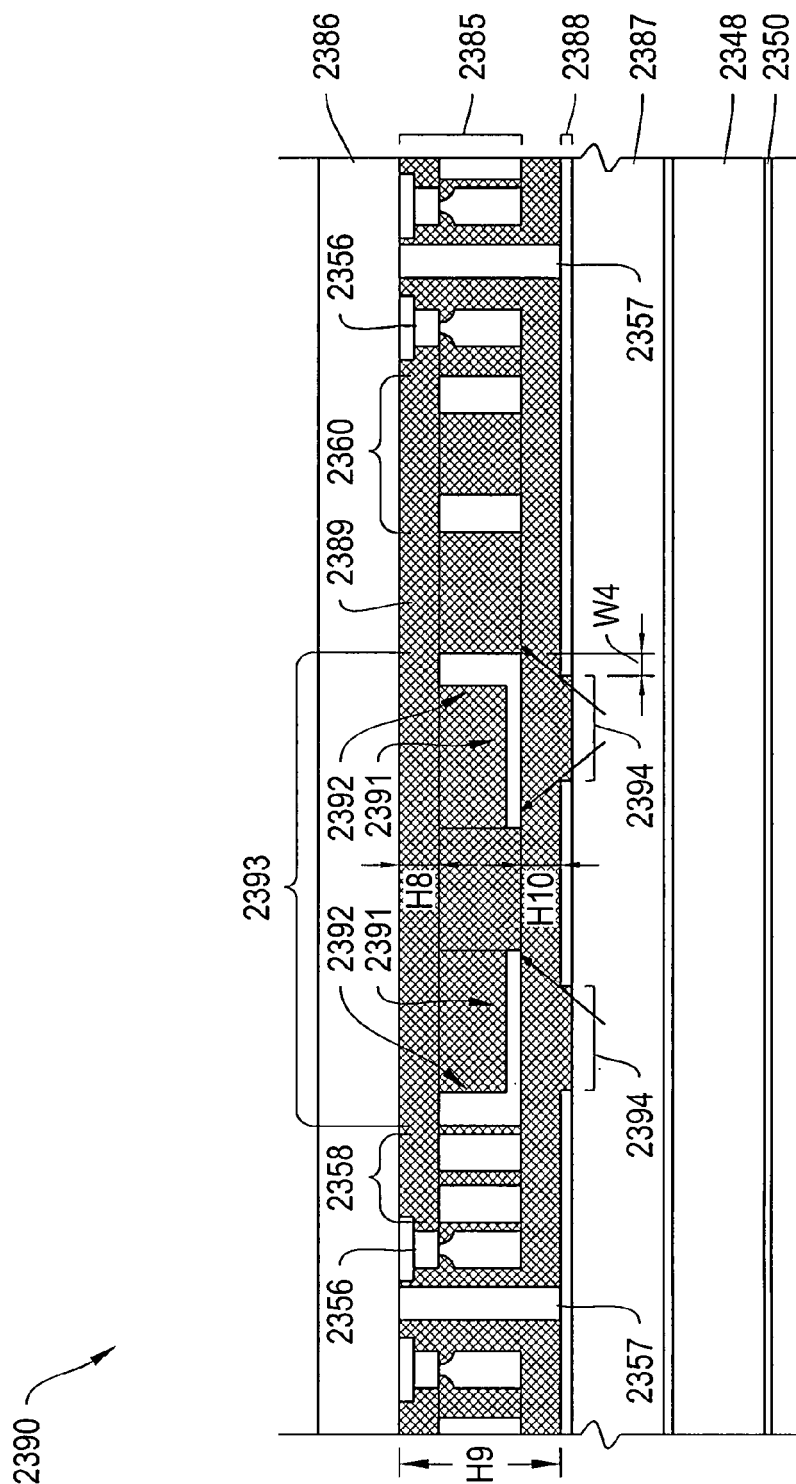


Figure 7D



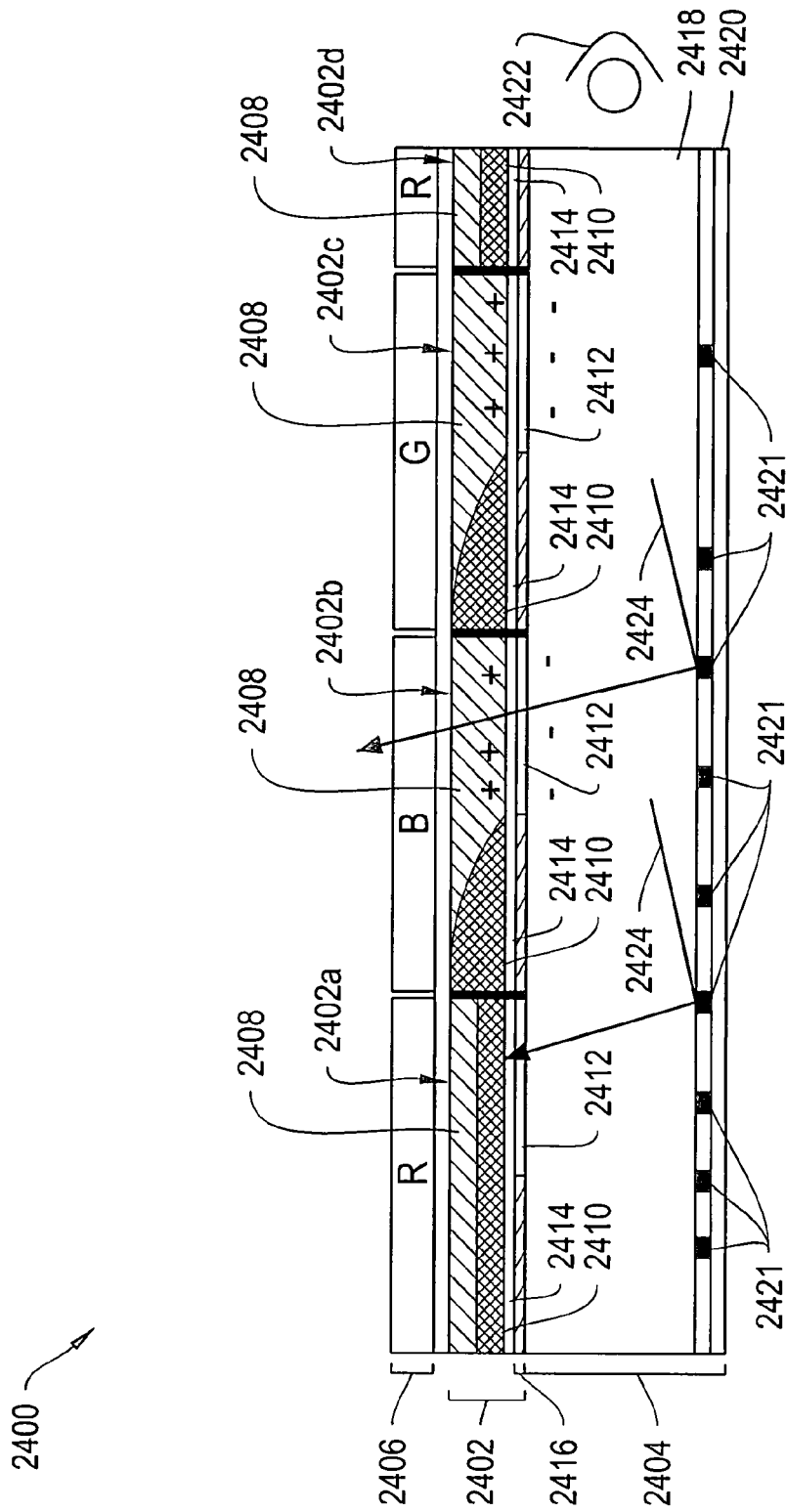


Figure 8

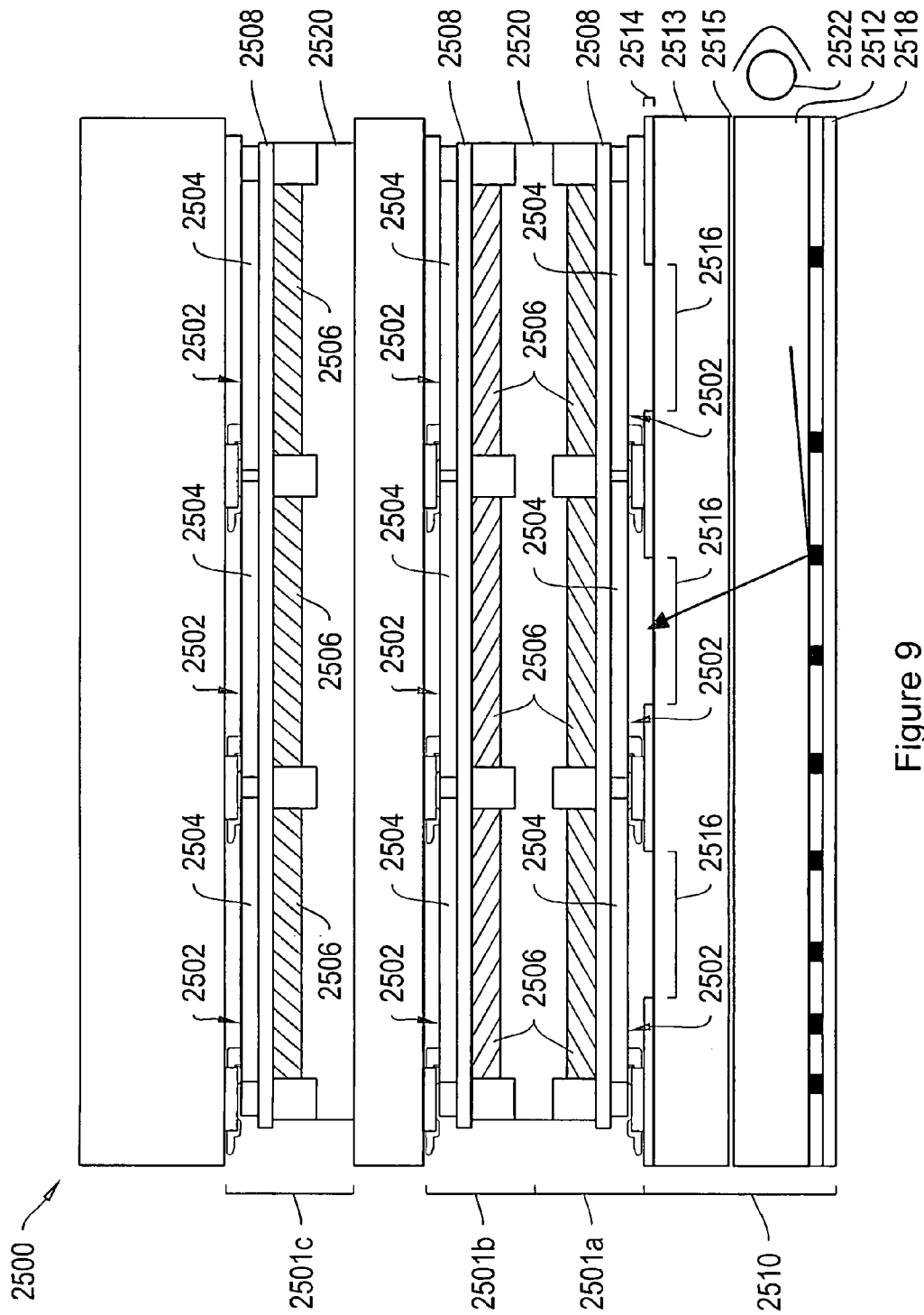


Figure 9

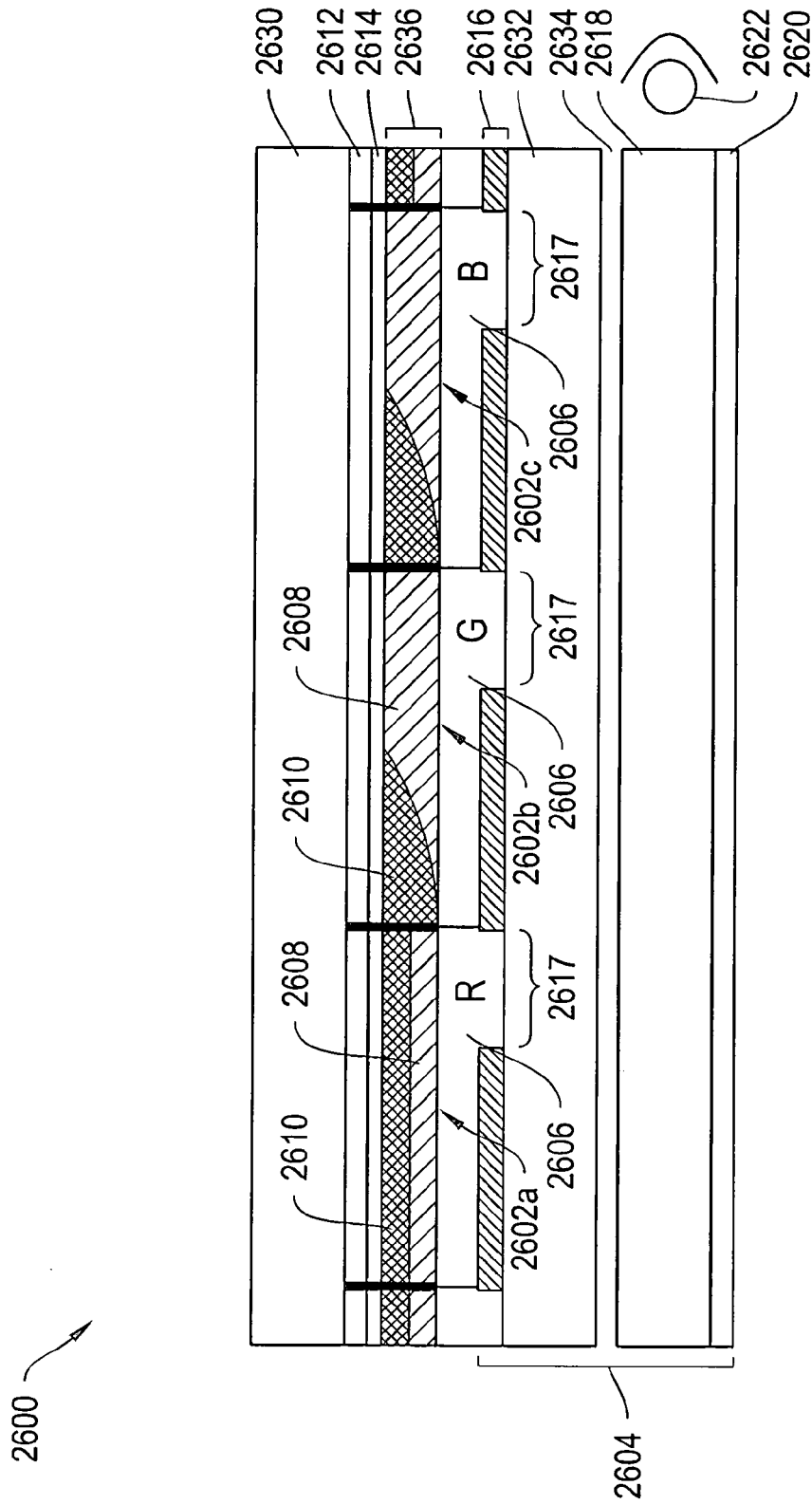


Figure 10

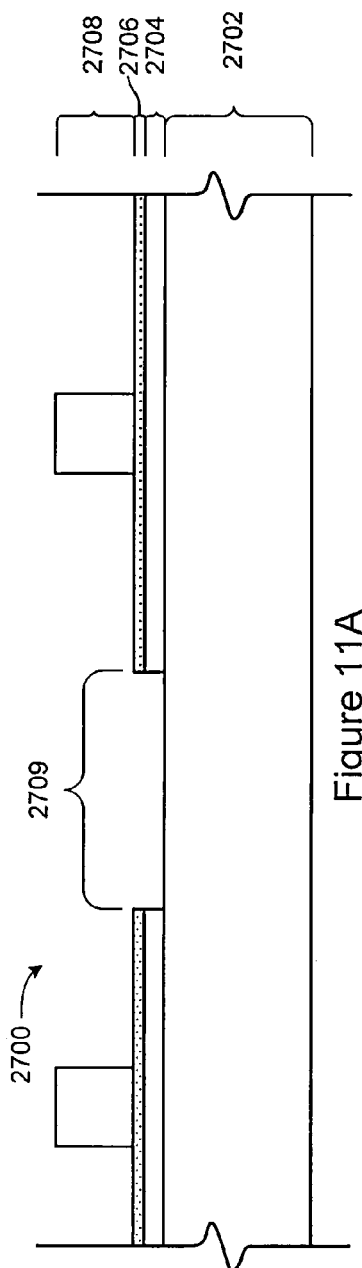


Figure 11A

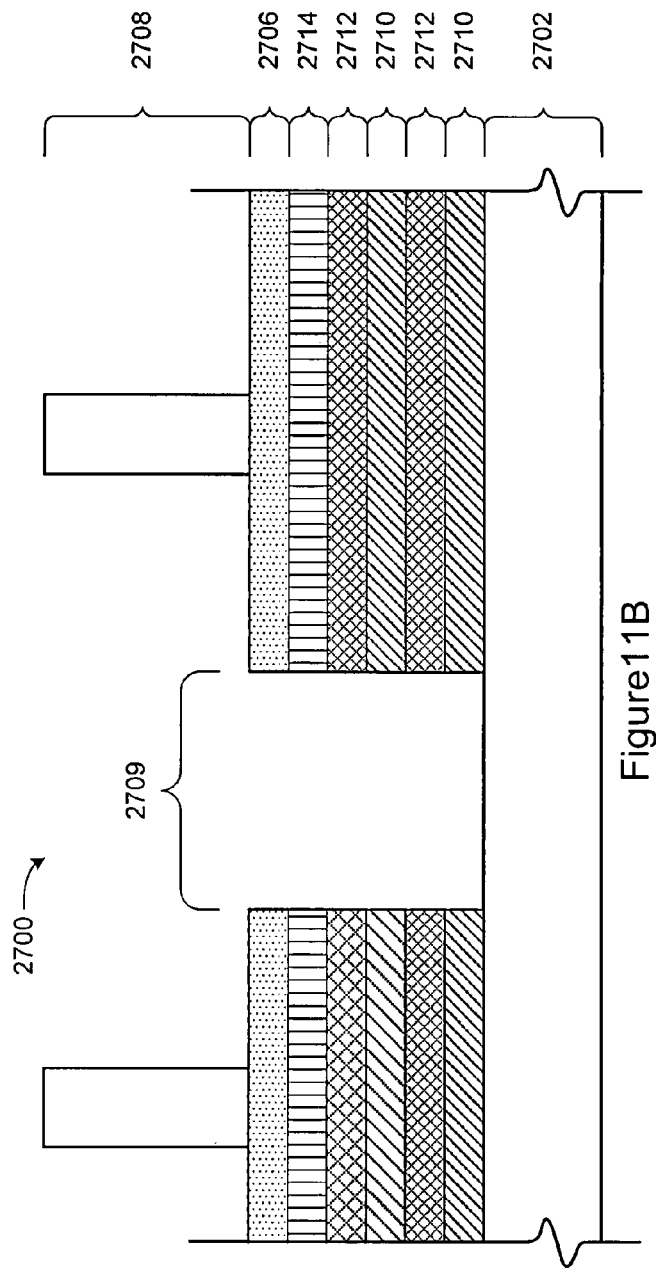


Figure 11B

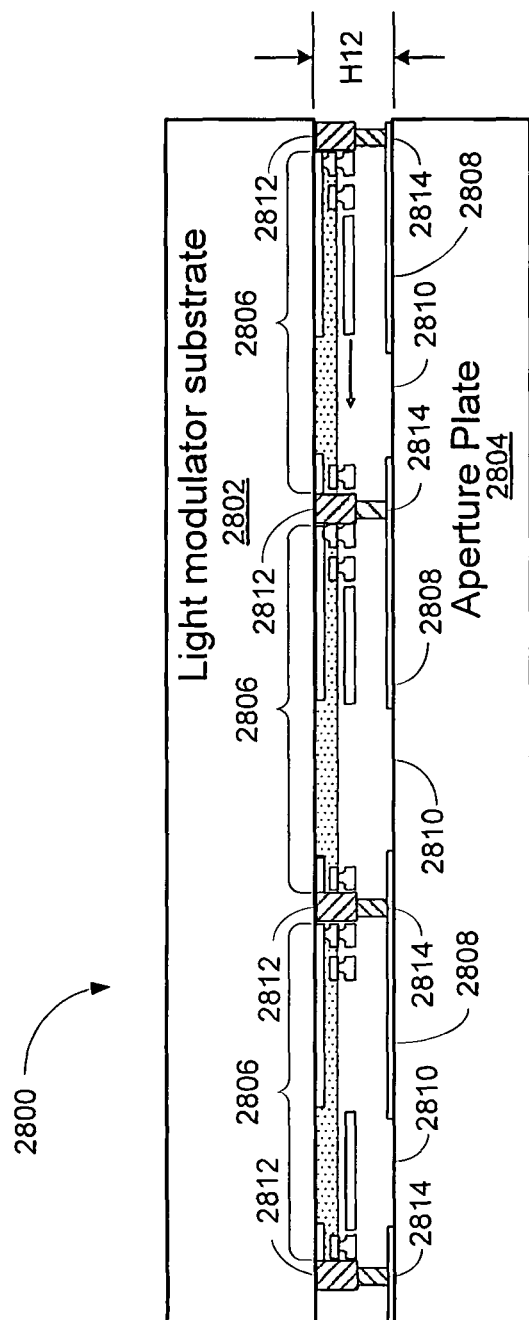


Figure 12

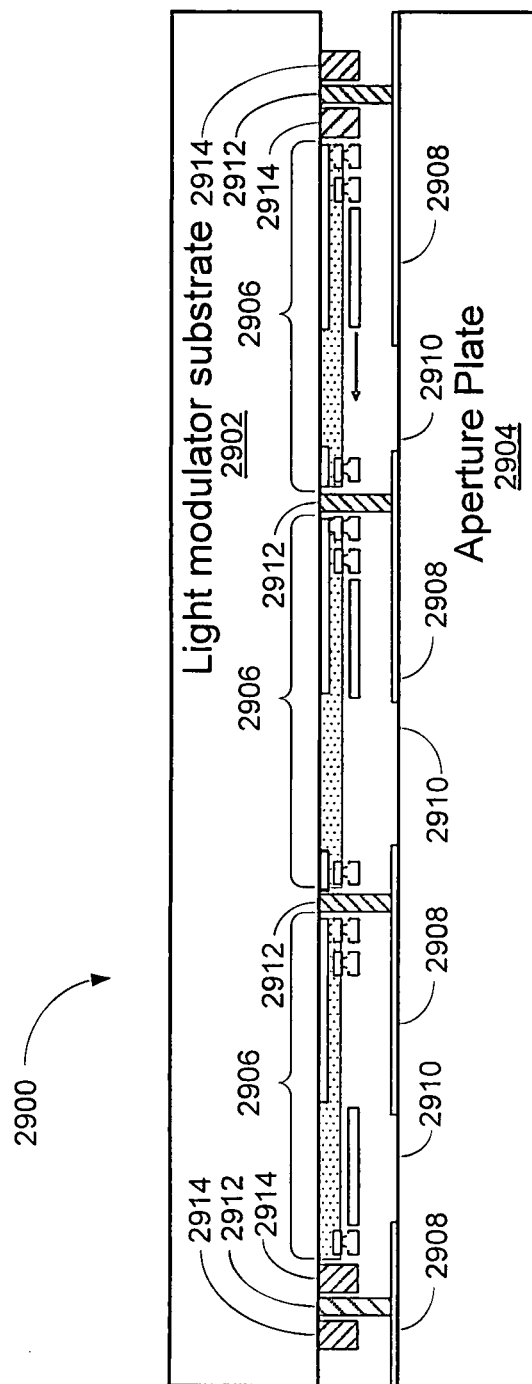


Figure 13A

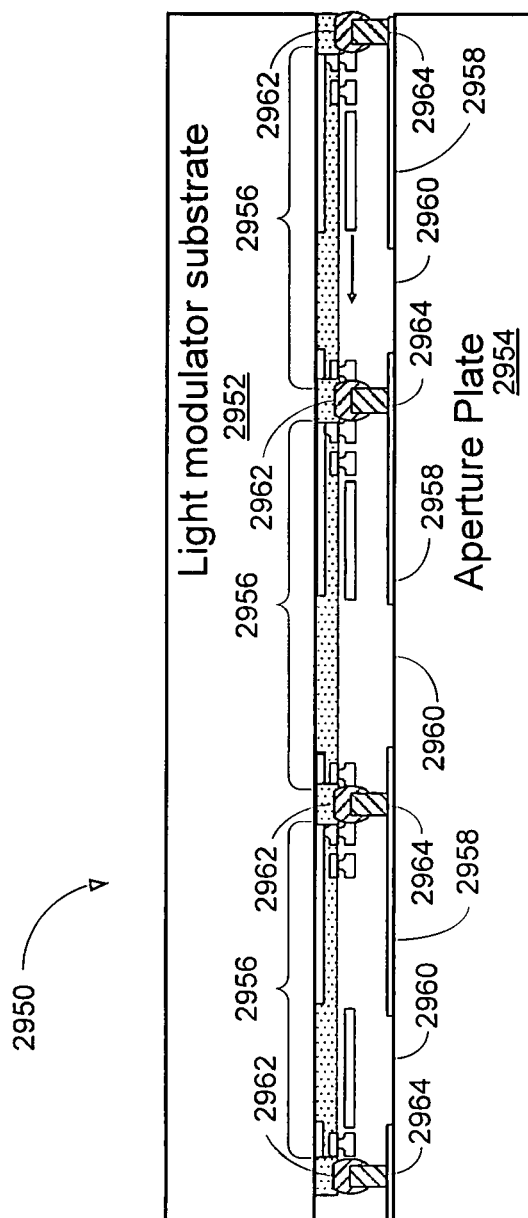


Figure 13B

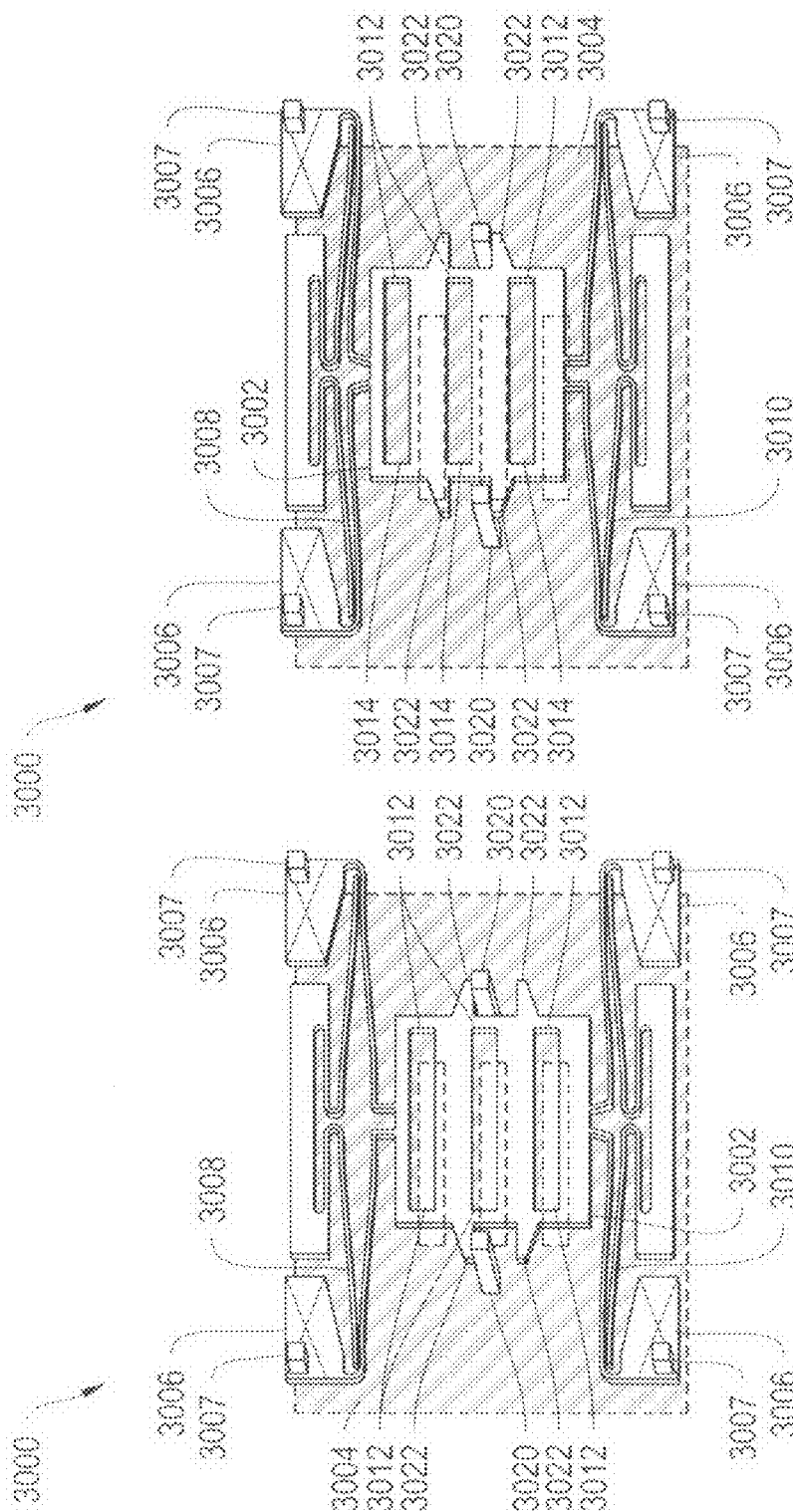


Figure 14B

Figure 14A



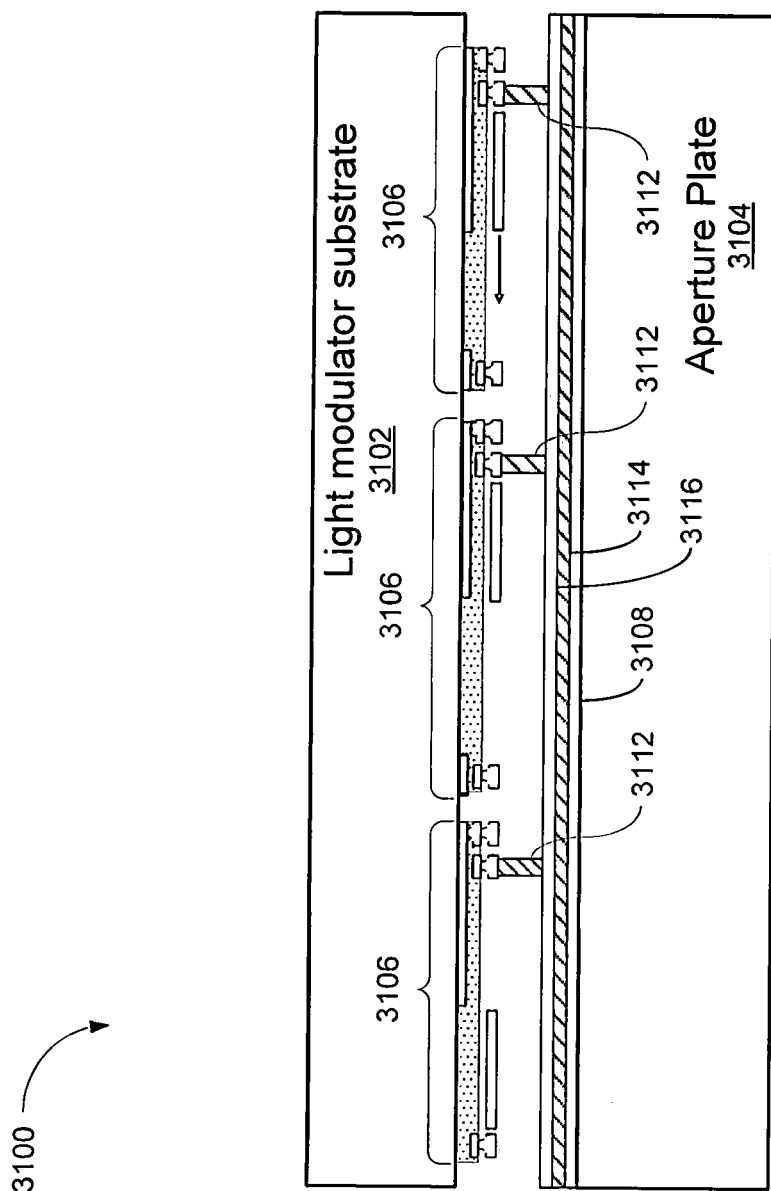


Figure 15

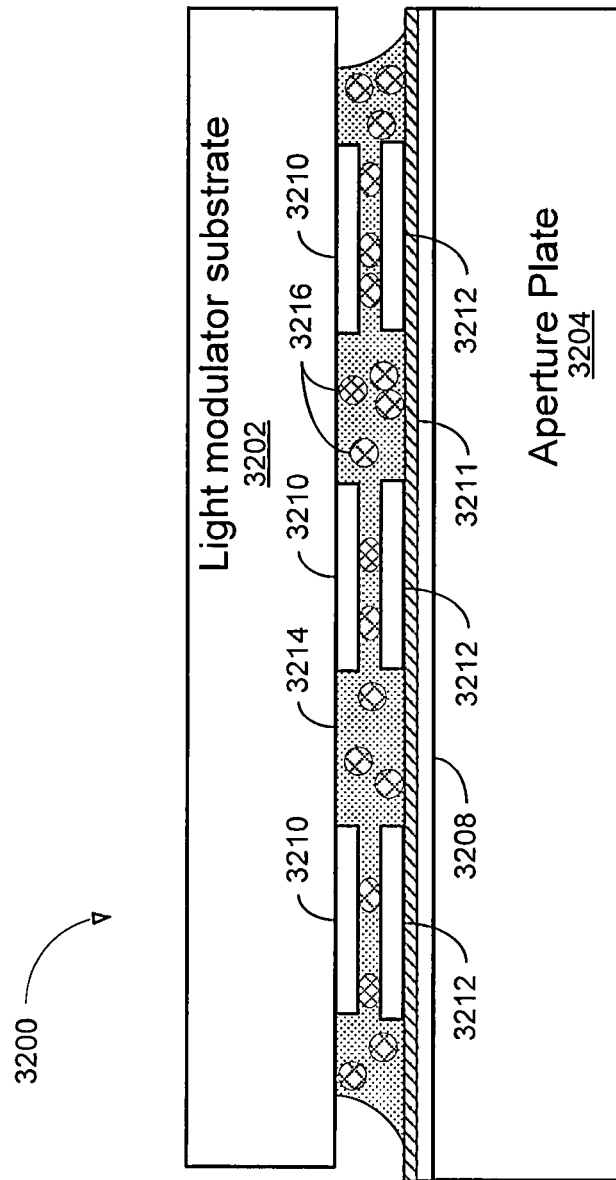


Figure 16

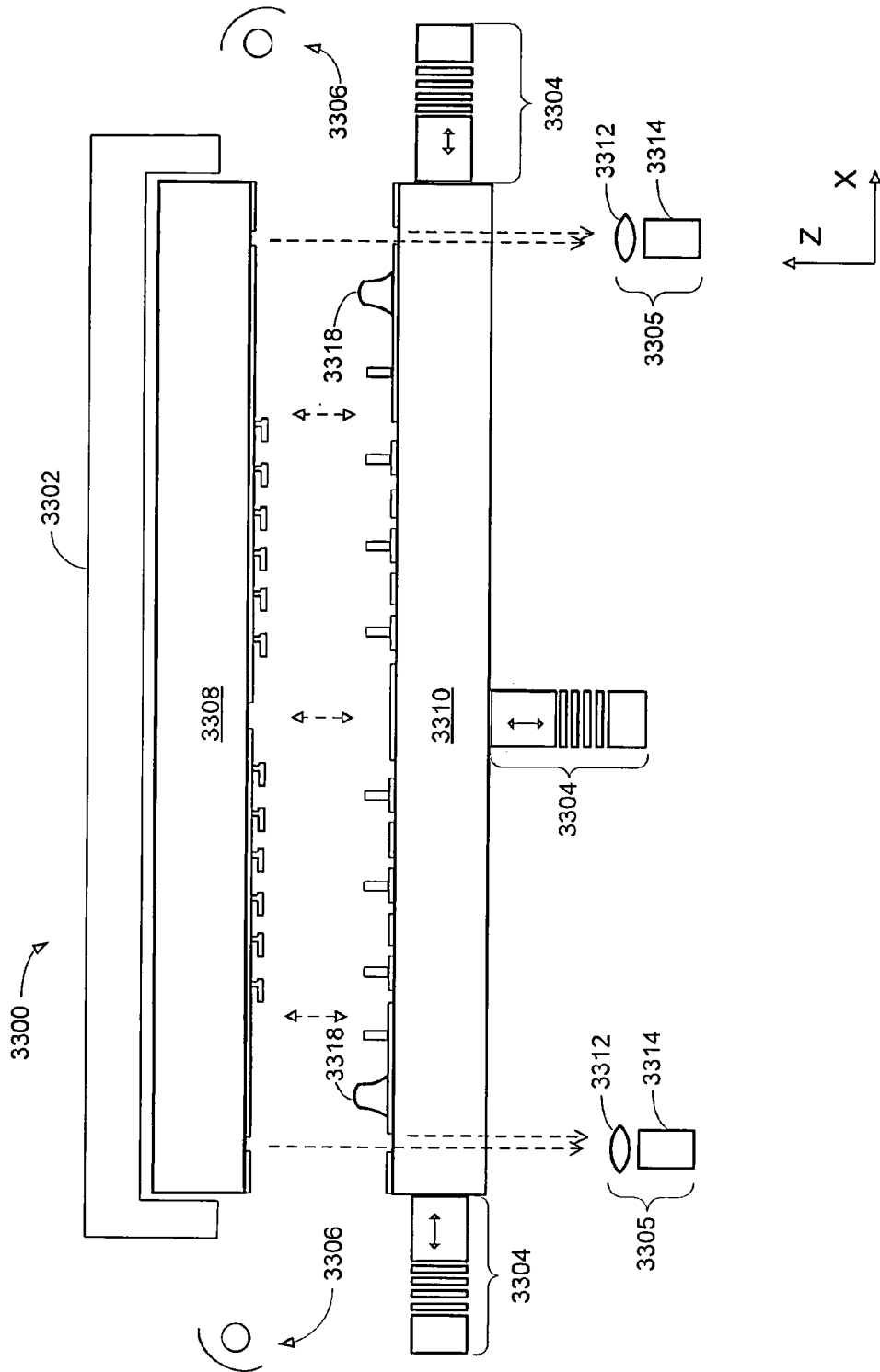


FIGURE 17

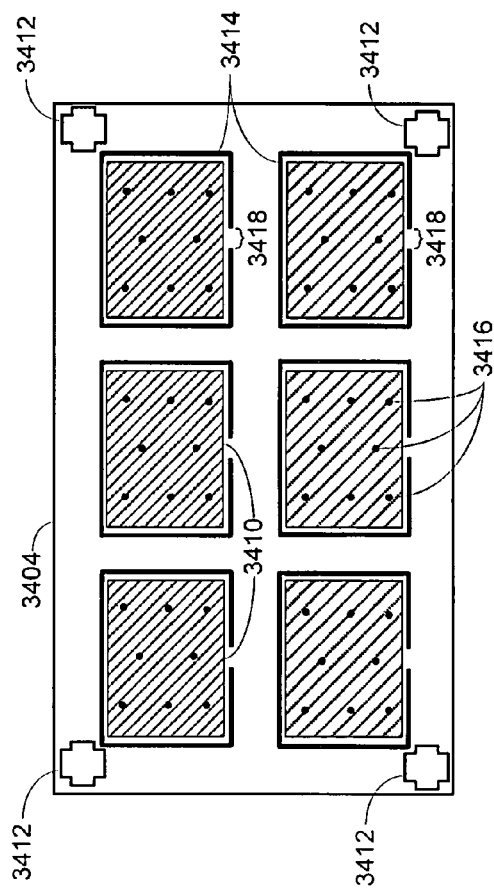
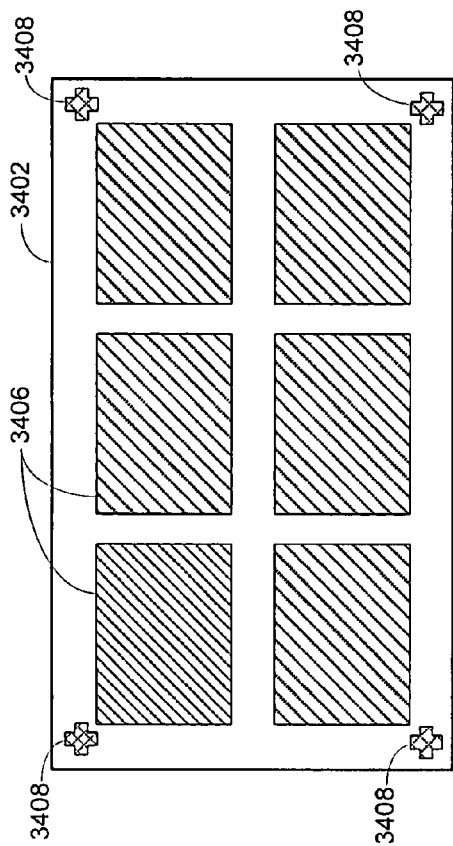


FIGURE 18

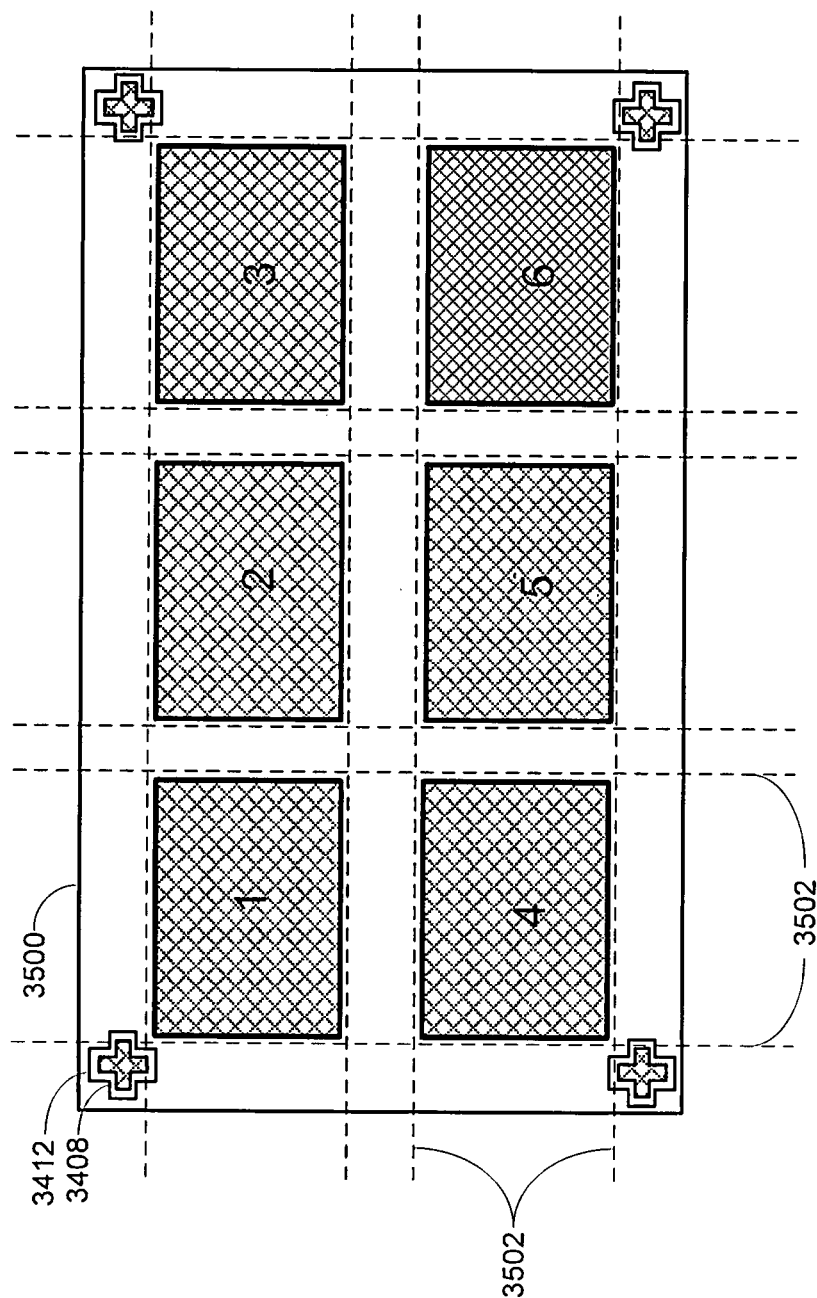


FIGURE 19

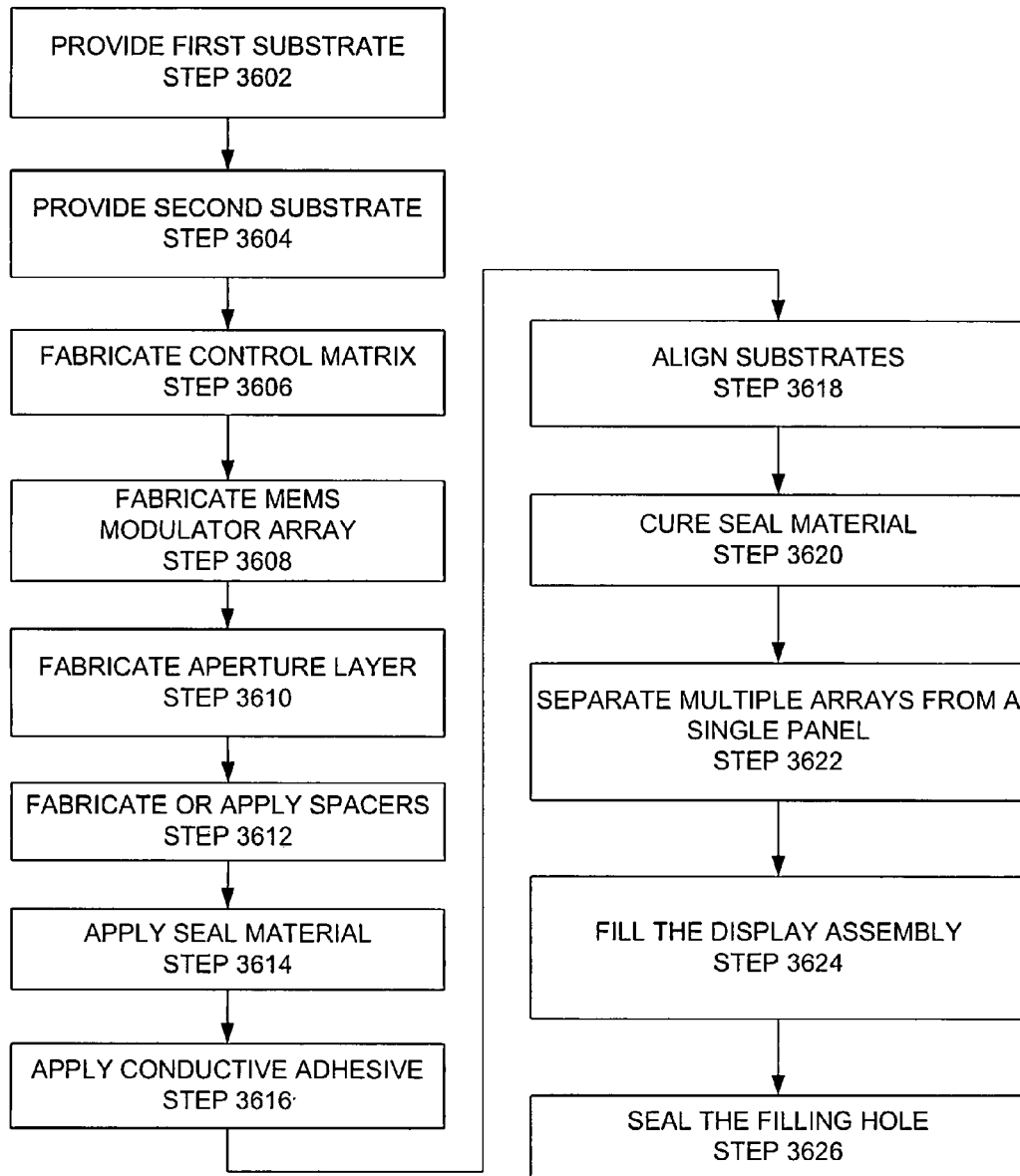


FIGURE 20

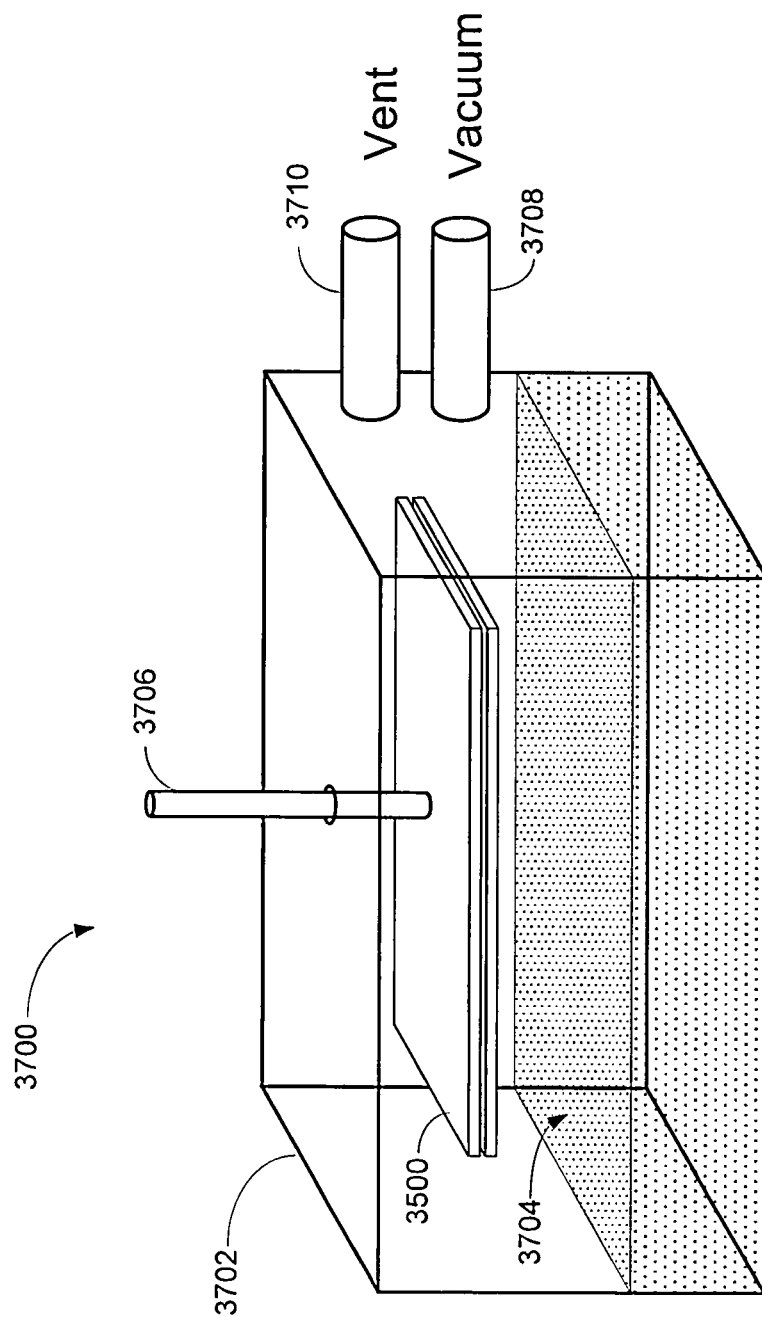


FIGURE 21

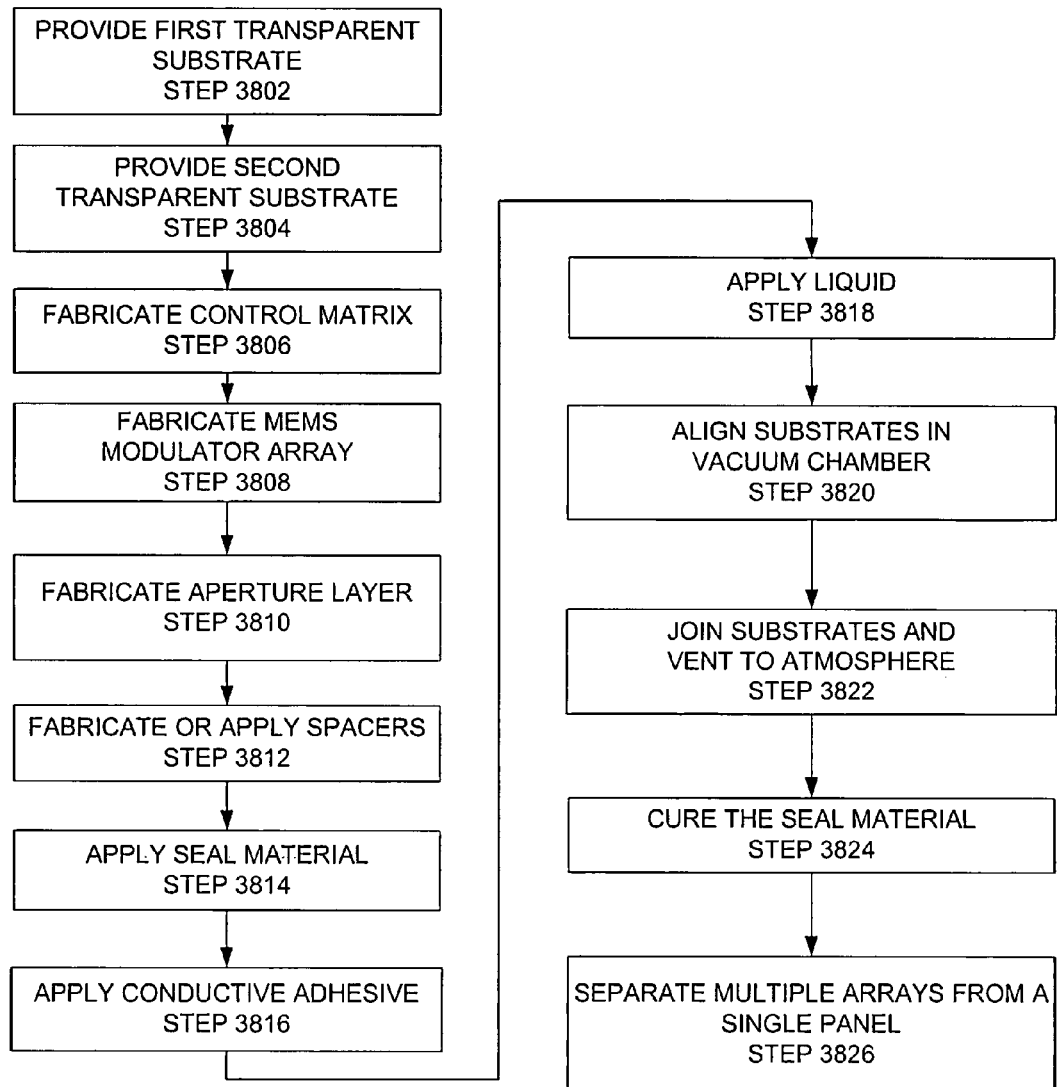


FIGURE 22



# ALIGNMENT METHODS IN FLUID-FILLED MEMS DISPLAYS

## CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims priority to and benefit of U.S. Provisional Patent Application No. 60/930,872, entitled "MEMS Displays and Assembly Methods" and filed on May 18, 2007, and is a continuation-in-part of U.S. patent application Ser. No. 11/656,307, entitled "Methods and Apparatus for Actuating Displays" and filed on Jan. 19, 2007, which is a continuation-in-part of U.S. patent application Ser. No. 11/251,035, entitled "Methods and Apparatus for Actuating Displays" and filed on Oct. 14, 2005, which is a continuation-in-part of U.S. patent application Ser. No. 11/218,690, entitled "Methods and Apparatus for Spatial Light Modulation" and filed on Sep. 2, 2005, which claims priority to and benefit of U.S. Provisional Patent Application No. 60/676,053, entitled "MEMS Based Optical Display" and filed on Apr. 29, 2005, and U.S. Provisional Application 60/655,827, entitled "MEMS Based Display Modules" and filed on Feb. 23, 2005. This application is also a continuation-in-part of U.S. patent application Ser. No. 11/218,690, entitled "Methods and Apparatus for Spatial Light Modulation" and filed on Sep. 2, 2005, which claims priority to and benefit of U.S. Provisional Patent Application No. 60/676,053, entitled "MEMS Based Optical Display" and filed on Apr. 29, 2005, and U.S. Provisional Application 60/655,827, entitled "MEMS Based Display Modules" and filed on Feb. 23, 2005. The entirety of each of these provisional and non-provisional applications is incorporated by reference herein.

## FIELD OF THE INVENTION

In general, the invention relates to the field of assembly of imaging displays, in particular, the invention relates to the assembly of mechanically actuated display apparatus.

## BACKGROUND OF THE INVENTION

Displays built from mechanical light modulators are an attractive alternative to displays based on liquid crystal technology. Mechanical light modulators are fast enough to display video content with good viewing angles and with a wide range of color and grey scale. Mechanical light modulators have been successful in projection display applications. Backlit displays using mechanical light modulators have not yet demonstrated sufficiently attractive combinations of brightness and low power. There is a need in the art for fast, bright, low-powered mechanically actuated displays.

Unlike in liquid crystal displays, MEMS-based displays include hundreds, thousands, or in some cases, millions of moving elements. In some devices, every movement of an element provides an opportunity for stiction to disable one or more of the elements. In addition, effective operation of MEMS-based displays depends on the coupling of optical, electrical, and/or mechanical components. Misalignment of such components can lead to inferior picture quality and potentially even inoperability of the display as a whole.

## SUMMARY OF THE INVENTION

Thus a need exists in the art to be able to precisely align the various substrates that make up a MEMS display. At least in part to address this need, in one aspect, the invention relates to a method of manufacturing a display assembly. The method

includes providing a first substrate on which a plurality of MEMS light modulators has been fabricated. The first substrate may be opaque or transparent. Each light modulator has a light and a dark state. The method also includes providing a second substrate, which is preferably transparent, that includes a layer in which a plurality of apertures is formed. In one embodiment, the layer is reflective. In other embodiments, the layer is light-absorbing. The first and second substrates are then aligned to establish a correspondence between respective light modulators and apertures.

The MEMS light modulators include modulation elements, for example, shutters, light taps, oils, or interference modulators, which have at least one edge. Each aperture also has an edge. In one embodiment, the first and substrates are aligned such that when light modulators are in a dark state, an edge of their respective light modulation elements overlap an edge of a corresponding aperture by more than 0 microns and less than about 20 microns. In another embodiment, the edges of the light modulators, in a dark state, overlap edges of the apertures by more than 0 microns but less than about 5 microns.

The alignment may be maintained in a number of ways. It can be maintained by bonding the first substrate to the second substrate with an adhesive or a heat reflowable material, or by coupling interlocking features formed on or in the first and second substrates.

The assembly process can handle the manufacture of individual display assemblies, or multiple display assemblies in parallel. In the latter case, the plurality of MEMS modulators on the first substrate includes multiple arrays of MEMS modulators positioned on a panel. The plurality of apertures on the second substrate likewise includes corresponding multiple arrays of apertures. When manufacturing multiple display assemblies from a single panel, the assembly process including singulating the display panels. The singulation of the substrates can be carried out before or after they are aligned and/or sealed.

To align the substrates, alignment marks can be formed on each of the first and second substrates. The substrates can then be loaded into an alignment apparatus that includes a vision system for monitoring misalignment between alignment marks. The alignment apparatus also includes motors or drives for adjusting the relative positions of the two substrates. The alignment apparatus may also include UV lamps for curing adhesive materials.

In one embodiment, the alignment method includes applying spacers to one of the substrates to establish a fixed separation between the substrates. The spacers may be formed from a conductive material to bridge a gap between the two substrates.

In addition, stiction can be reduced by having the surfaces of the display components (including front and rear surfaces of moving elements) wetted by a fluid, such as a lubricant. Various liquids and gases, when surrounding moving components of MEMS light modulators, in addition to reducing stiction, can also provide improved optical and electromechanical performance of a display.

Accordingly, according to another aspect, the invention relates to a display assembly that includes an array of light modulators having elements that are substantially surrounded by, and preferably move through, a liquid, such as a lubricant. The array of light modulators are formed on a first substrate. The first substrate is sealed with an adhesive to a second, transparent substrate, to contain the liquid surrounding the MEMS light modulators. The seal also acts to restrict relative motion between the two substrates. In one embodiment, the seal is formed from a polymer material.

The liquid sealed in the display assembly has a first index of refraction and the substrate on which the aperture layer is disposed has a second index of refraction. In one embodiment, the first index of refraction is greater than or substantially equal to that of the second index of refraction. The liquid is also preferably non-conductive and has a dielectric constant that is greater than 2.0.

#### BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing discussion will be understood more readily from the following detailed description of the invention with reference to the following drawings:

FIG. 1A is an isometric view of display apparatus, according to an illustrative embodiment of the invention;

FIG. 1B is a block diagram of the display apparatus of FIG. 1A, according to an illustrative embodiment of the invention;

FIG. 2A is a perspective view of an illustrative shutter-based light modulator suitable for incorporation into the MEMS-based display of FIG. 1A, according to an illustrative embodiment of the invention;

FIG. 2B is a cross-sectional view of a rollershade-based light modulator suitable for incorporation into the MEMS-based display of FIG. 1A, according to an illustrative embodiment of the invention;

FIG. 2C is a cross sectional view of a light-tap-based light modulator suitable for incorporation into an alternative embodiment of the MEMS-based display of FIG. 1A, according to an illustrative embodiment of the invention;

FIG. 3 is a schematic diagram of a control matrix suitable for controlling the light modulators incorporated into the MEMS-based display of FIG. 1A, according to an illustrative embodiment of the invention;

FIG. 4 is a perspective view of an array of shutter-based light modulators connected to the control matrix of FIG. 3, according to an illustrative embodiment of the invention;

FIG. 5 is cross-sectional view of a display apparatus, according to an illustrative embodiment of the invention;

FIGS. 6A and 6B are top views of the shutter assembly of FIG. 8 in open and closed states, respectively, according to an illustrative embodiment of the invention;

FIGS. 7A-7D are cross sectional views of shutter assemblies having shutters, which, when in a closed position, overlap apertures formed in an adjacent reflective surface, according to an illustrative embodiment of the invention;

FIG. 8 is a cross sectional view of a first electrowetting-based light modulation array, according to an illustrative embodiment of the invention;

FIG. 9 is a cross sectional view of a second electrowetting-based light modulation array, according to an illustrative embodiment of the invention; and

FIG. 10 is a cross sectional view of a third electrowetting-based light modulation array, according to an illustrative embodiment of the invention.

FIGS. 11A and 11B are cross sectional views of an aperture plate, according to an illustrative embodiment of the invention.

FIG. 12 is a cross sectional view of a display assembly, according to an illustrative embodiment of the invention.

FIG. 13A is a cross sectional view of a display assembly, according to an illustrative embodiment of the invention.

FIG. 13B is a cross sectional view of a display assembly, according to an illustrative embodiment of the invention.

FIGS. 14A and 14B are perspective views of a shutter assembly in open and closed states, respectively, according to an illustrative embodiment of the invention.

FIG. 15 is a cross sectional view of a display assembly, according to an illustrative embodiment of the invention.

FIG. 16 is a cross sectional view of a display assembly, according to an illustrative embodiment of the invention.

FIG. 17 is a conceptual view of a precision substrate alignment apparatus, according to an illustrative embodiment of the invention.

FIG. 18 is a plan view of a modulator substrate and an aperture plate comprising multiple modulator and aperture arrays respectively, according to an illustrative embodiment of the invention.

FIG. 19 is a plan view of a panel assembly after alignment, according to an illustrative embodiment of the invention.

FIG. 20 is a flow chart of a cell assembly method, according to an illustrative embodiment of the invention.

FIG. 21 is conceptual view of a fluid filling apparatus, according to an illustrative embodiment of the invention.

FIG. 22 is a flow chart of a cell assembly method, according to an illustrative embodiment of the invention.

#### DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

To provide an overall understanding of the invention, certain illustrative embodiments will now be described, including apparatus and methods for displaying images. However, it will be understood by one of ordinary skill in the art that the systems and methods described herein may be adapted and modified as is appropriate for the application being addressed and that the systems and methods described herein may be employed in other suitable applications, and that such other additions and modifications will not depart from the scope hereof.

FIG. 1A is a schematic diagram of a direct-view MEMS-based display apparatus **100**, according to an illustrative embodiment of the invention. The display apparatus **100** includes a plurality of light modulators **102a-102d** (generally "light modulators **102**") arranged in rows and columns. In the display apparatus **100**, light modulators **102a** and **102d** are in the open state, allowing light to pass. Light modulators **102b** and **102c** are in the closed state, obstructing the passage of light. By selectively setting the states of the light modulators **102a-102d**, the display apparatus **100** can be utilized to form an image **104** for a backlit display, if illuminated by a lamp or lamps **105**. In another implementation, the apparatus **100** may form an image by reflection of ambient light originating from the front of the apparatus. In another implementation, the apparatus **100** may form an image by reflection of light from a lamp or lamps positioned in the front of the display, i.e. by use of a frontlight. In one of the closed or open states, the light modulators **102** interfere with light in an optical path by, for example, and without limitation, blocking, reflecting, absorbing, filtering, polarizing, diffracting, or otherwise altering a property or path of the light.

In the display apparatus **100**, each light modulator **102** corresponds to a pixel **106** in the image **104**. In other implementations, the display apparatus **100** may utilize a plurality of light modulators to form a pixel **106** in the image **104**. For example, the display apparatus **100** may include three color-specific light modulators **102**. By selectively opening one or more of the color-specific light modulators **102** corresponding to a particular pixel **106**, the display apparatus **100** can generate a color pixel **106** in the image **104**. In another example, the display apparatus **100** includes two or more light modulators **102** per pixel **106** to provide grayscale in an image **104**. With respect to an image, a "pixel" corresponds to the smallest picture element defined by the resolution of the

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image. With respect to structural components of the display apparatus **100**, the term “pixel” refers to the combined mechanical and electrical components utilized to modulate the light that forms a single pixel of the image.

Display apparatus **100** is a direct-view display in that it does not require imaging optics. The user sees an image by looking directly at the display apparatus **100**. In alternate embodiments the display apparatus **100** is incorporated into a projection display. In such embodiments, the display forms an image by projecting light onto a screen or onto a wall. In projection applications the display apparatus **100** is substantially smaller than the projected image **104**.

Direct-view displays may operate in either a transmissive or reflective mode. In a transmissive display, the light modulators filter or selectively block light which originates from a lamp or lamps positioned behind the display. The light from the lamps is optionally injected into a light guide or “backlight”. Transmissive direct-view display embodiments are often built onto transparent or glass substrates to facilitate a sandwich assembly arrangement where one substrate, containing the light modulators, is positioned directly on top of the backlight. In some transmissive display embodiments, a color-specific light modulator is created by associating a color filter material with each modulator **102**. In other transmissive display embodiments colors can be generated, as described below, using a field sequential color method by alternating illumination of lamps with different primary colors.

Each light modulator **102** includes a shutter **108** and an aperture **109**. To illuminate a pixel **106** in the image **104**, the shutter **108** is positioned such that it allows light to pass through the aperture **109** towards a viewer. To keep a pixel **106** unlit, the shutter **108** is positioned such that it obstructs the passage of light through the aperture **109**. The aperture **109** is defined by an opening patterned through a reflective or light-absorbing material.

The display apparatus also includes a control matrix connected to the substrate and to the light modulators for controlling the movement of the shutters. The control matrix includes a series of electrical interconnects (e.g., interconnects **110**, **112**, and **114**), including at least one write-enable interconnect **110** (also referred to as a “scan-line interconnect”) per row of pixels, one data interconnect **112** for each column of pixels, and one common interconnect **114** providing a common voltage to all pixels, or at least to pixels from both multiple columns and multiples rows in the display apparatus **100**. In response to the application of an appropriate voltage (the “write-enabling voltage,  $V_{we}$ ”), the write-enable interconnect **110** for a given row of pixels prepares the pixels in the row to accept new shutter movement instructions. The data interconnects **112** communicate the new movement instructions in the form of data voltage pulses. The data voltage pulses applied to the data interconnects **112**, in some implementations, directly contribute to an electrostatic movement of the shutters. In other implementations, the data voltage pulses control switches, e.g., transistors or other non-linear circuit elements that control the application of separate actuation voltages, which are typically higher in magnitude than the data voltages, to the light modulators **102**. The application of these actuation voltages then results in the electrostatic driven movement of the shutters **108**.

FIG. 1B is a block diagram **150** of the display apparatus **100**. Referring to FIGS. 1A and 1B, in addition to the elements of the display apparatus **100** described above, as depicted in the block diagram **150**, the display apparatus **100** includes a plurality of scan drivers **152** (also referred to as “write enabling voltage sources”) and a plurality of data

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drivers **154** (also referred to as “data voltage sources”). The scan drivers **152** apply write enabling voltages to scan-line interconnects **110**. The data drivers **154** apply data voltages to the data interconnects **112**. In some embodiments of the display apparatus, the data drivers **154** are configured to provide analog data voltages to the light modulators, especially where the gray scale of the image **104** is to be derived in analog fashion. In analog operation the light modulators **102** are designed such that when a range of intermediate voltages is applied through the data interconnects **112** there results a range of intermediate open states in the shutters **108** and therefore a range of intermediate illumination states or gray scales in the image **104**.

In other cases the data drivers **154** are configured to apply only a reduced set of 2, 3, or 4 digital voltage levels to the control matrix. These voltage levels are designed to set, in digital fashion, either an open state or a closed state to each of the shutters **108**.

The scan drivers **152** and the data drivers **154** are connected to digital controller circuit **156** (also referred to as the “controller **156**”). The controller **156** includes an input processing module **158**, which processes an incoming image signal **157** into a digital image format appropriate to the spatial addressing and the gray scale capabilities of the display **100**. The pixel location and gray scale data of each image is stored in a frame buffer **159** so that the data can be fed out as needed to the data drivers **154**. The data is sent to the data drivers **154** in mostly serial fashion, organized in predetermined sequences grouped by rows and by image frames. The data drivers **154** can include series to parallel data converters, level shifting, and for some applications digital to analog voltage converters.

The display **100** apparatus optionally includes a set of common drivers **153**, also referred to as common voltage sources. In some embodiments the common drivers **153** provide a DC common potential to all light modulators within the array of light modulators **103**, for instance by supplying voltage to a series of common interconnects **114**. In other embodiments the common drivers **153**, following commands from the controller **156**, issue voltage pulses or signals to the array of light modulators **103**, for instance global actuation pulses which are capable of driving and/or initiating simultaneous actuation of all light modulators in multiple rows and columns of the array **103**.

All of the drivers (e.g., scan drivers **152**, data drivers **154**, and common drivers **153**) for different display functions are time-synchronized by a timing-control module **160** in the controller **156**. Timing commands from the module **160** coordinate the illumination of red, green and blue and white lamps (**162**, **164**, **166**, and **167** respectively) via lamp drivers **168**, the write-enabling and sequencing of specific rows within the array of pixels **103**, the output of voltages from the data drivers **154**, and the output of voltages that provide for light modulator actuation.

The controller **156** determines the sequencing or addressing scheme by which each of the shutters **108** in the array **103** can be re-set to the illumination levels appropriate to a new image **104**. Details of suitable addressing, image formation, and gray scale techniques can be found in U.S. patent application Ser. Nos. 11/326,696 and 11/643,042, incorporated herein by reference. New images **104** can be set at periodic intervals. For instance, for video displays, the color images **104** or frames of video are refreshed at frequencies ranging from 10 to 300 Hertz. In some embodiments the setting of an image frame to the array **103** is synchronized with the illumination of the lamps **162**, **164**, and **166** such that alternate image frames are illuminated with an alternating series of

colors, such as red, green, and blue. The image frames for each respective color is referred to as a color sub-frame. In this method, referred to as the field sequential color method, if the color sub-frames are alternated at frequencies in excess of 20 Hz, the human brain will average the alternating frame images into the perception of an image having a broad and continuous range of colors. In alternate implementations, four or more lamps with primary colors can be employed in display apparatus **100**, employing primaries other than red, green, and blue.

In some implementations, where the display apparatus **100** is designed for the digital switching of shutters **108** between open and closed states, the controller **156** determines the addressing sequence and/or the time intervals between image frames to produce images **104** with appropriate gray scale. The process of generating varying levels of grayscale by controlling the amount of time a shutter **108** is open in a particular frame is referred to as time division gray scale. In one embodiment of time division gray scale, the controller **156** determines the time period or the fraction of time within each frame that a shutter **108** is allowed to remain in the open state, according to the illumination level or gray scale desired of that pixel. In other implementations, for each image frame, the controller **156** sets a plurality of sub-frame images in multiple rows and columns of the array **103**, and the controller alters the duration over which each sub-frame image is illuminated in proportion to a gray scale value or significance value employed within a coded word for gray scale. For instance, the illumination times for a series of sub-frame images can be varied in proportion to the binary coding series 1, 2, 4, 8 . . . . The shutters **108** for each pixel in the array **103** are then set to either the open or closed state within a sub-frame image according to the value at a corresponding position within the pixel's binary coded word for gray level.

In other implementations, the controller alters the intensity of light from the lamps **162**, **164**, and **166** in proportion to the gray scale value desired for a particular sub-frame image. A number of hybrid techniques are also available for forming colors and gray scale from an array of shutters **108**. For instance, the time division techniques described above can be combined with the use of multiple shutters **108** per pixel, or the gray scale value for a particular sub-frame image can be established through a combination of both sub-frame timing and lamp intensity. Details of these and other embodiments can be found in U.S. patent application Ser. No. 11/643,042, referenced above.

In some implementations the data for an image state **104** is loaded by the controller **156** to the modulator array **103** by a sequential addressing of individual rows, also referred to as scan lines. For each row or scan line in the sequence, the scan driver **152** applies a write-enable voltage to the write enable interconnect **110** for that row of the array **103**, and subsequently the data driver **154** supplies data voltages, corresponding to desired shutter states, for each column in the selected row. This process repeats until data has been loaded for all rows in the array. In some implementations the sequence of selected rows for data loading is linear, proceeding from top to bottom in the array. In other implementations the sequence of selected rows is pseudo-randomized, in order to minimize visual artifacts. And in other implementations the sequencing is organized by blocks, where, for a block, the data for only a certain fraction of the image state **104** is loaded to the array, for instance by addressing only every 5<sup>th</sup> row of the array in sequence.

In some implementations, the process for loading image data to the array **103** is separated in time from the process of actuating the shutters **108**. In these implementations, the

modulator array **103** may include data memory elements for each pixel in the array **103** and the control matrix may include a global actuation interconnect for carrying trigger signals, from common driver **153**, to initiate simultaneous actuation of shutters **108** according to data stored in the memory elements. Various addressing sequences, many of which are described in U.S. patent application Ser. No. 11/643,042, can be coordinated by means of the timing control module **160**.

In alternative embodiments, the array of pixels **103** and the control matrix that controls the pixels may be arranged in configurations other than rectangular rows and columns. For example, the pixels can be arranged in hexagonal arrays or curvilinear rows and columns. In general, as used herein, the term scan-line shall refer to any plurality of pixels that share a write-enabling interconnect.

The display **100** is comprised of a plurality of functional blocks including the timing control module **160**, the frame buffer **159**, scan drivers **152**, data drivers **154**, and drivers **153** and **168**. Each block can be understood to represent either a distinguishable hardware circuit and/or a module of executable code. In some implementations the functional blocks are provided as distinct chips or circuits connected together by means of circuit boards and/or cables. Alternately, many of these circuits can be fabricated along with the pixel array **103** on the same substrate of glass or plastic. In other implementations, multiple circuits, drivers, processors, and/or control functions from block diagram **150** may be integrated together within a single silicon chip, which is then bonded directly to the transparent substrate holding pixel array **103**.

The controller **156** includes a programming link **180** by which the addressing, color, and/or gray scale algorithms, which are implemented within controller **156**, can be altered according to the needs of particular applications. In some embodiments, the programming link **180** conveys information from environmental sensors, such as ambient light or temperature sensors, so that the controller **156** can adjust imaging modes or backlight power in correspondence with environmental conditions. The controller **156** also comprises a power supply input **182** which provides the power needed for lamps as well as light modulator actuation. Where necessary, the drivers **152**, **153**, **154**, and/or **168** may include or be associated with DC-DC converters for transforming an input voltage at **182** into various voltages sufficient for the actuation of shutters **108** or illumination of the lamps, such as lamps **162**, **164**, **166**, and **167**.

FIG. 2A is a perspective view of an illustrative shutter-based light modulator **200** suitable for incorporation into the MEMS-based display apparatus **100** of FIG. 1A, according to an illustrative embodiment of the invention. The shutter-based light modulator **200** (also referred to as shutter assembly **200**) includes a shutter **202** coupled to an actuator **204**. The actuator **204** is formed from two separate compliant electrode beam actuators **205** (the "actuators **205**"), as described in U.S. patent application Ser. No. 11/251,035, filed on Oct. 14, 2005. The shutter **202** couples on one side to the actuators **205**. The actuators **205** move the shutter **202** transversely over a surface **203** in a plane of motion which is substantially parallel to the surface **203**. The opposite side of the shutter **202** couples to a spring **207** which provides a restoring force opposing the forces exerted by the actuator **204**.

Each actuator **205** includes a compliant load beam **206** connecting the shutter **202** to a load anchor **208**. The load anchors **208** along with the compliant load beams **206** serve as mechanical supports, keeping the shutter **202** suspended proximate to the surface **203**. The load anchors **208** physically connect the compliant load beams **206** and the shutter

202 to the surface 203 and electrically connect the load beams 206 to a bias voltage, in some instances, ground.

Each actuator 205 also includes a compliant drive beam 216 positioned adjacent to each load beam 206. The drive beams 216 couple at one end to a drive beam anchor 218 shared between the drive beams 216. The other end of each drive beam 216 is free to move. Each drive beam 216 is curved such that it is closest to the load beam 206 near the free end of the drive beam 216 and the anchored end of the load beam 206.

The surface 203 includes one or more apertures 211 for admitting the passage of light. If the shutter assembly 200 is formed on an opaque substrate, made for example from silicon, then the surface 203 is a surface of the substrate, and the apertures 211 are formed by etching an array of holes through the substrate. If the shutter assembly 200 is formed on a transparent substrate, made for example of glass or plastic, then the surface 203 is a surface of a light blocking layer deposited on the substrate, and the apertures are formed by etching the surface 203 into an array of holes 211. The apertures 211 can be generally circular, elliptical, polygonal, serpentine, or irregular in shape.

In operation, a display apparatus incorporating the light modulator 200 applies an electric potential to the drive beams 216 via the drive beam anchor 218. A second electric potential may be applied to the load beams 206. The resulting potential difference between the drive beams 216 and the load beams 206 pulls the free ends of the drive beams 216 towards the anchored ends of the load beams 206, and pulls the shutter ends of the load beams 206 toward the anchored ends of the drive beams 216, thereby driving the shutter 202 transversely towards the drive anchor 218. The compliant members 206 act as springs, such that when the voltage across the beams 206 and 216 is removed, the load beams 206 push the shutter 202 back into its initial position, releasing the stress stored in the load beams 206.

The shutter assembly 200, also referred to as an elastic shutter assembly, incorporates a passive restoring force, such as a spring, for returning a shutter to its rest or relaxed position after voltages have been removed. A number of elastic restore mechanisms and various electrostatic couplings can be designed into or in conjunction with electrostatic actuators, the compliant beams illustrated in shutter assembly 200 being just one example. Other examples are described in U.S. patent application Ser. Nos. 11/251,035 and 11/326,696, incorporated herein by reference. For instance, a highly non-linear voltage-displacement response can be provided which favors an abrupt transition between “open” vs “closed” states of operation, and which, in many cases, provides a bi-stable or hysteretic operating characteristic for the shutter assembly. Other electrostatic actuators can be designed with more incremental voltage-displacement responses and with considerably reduced hysteresis, as may be preferred for analog gray scale operation.

The actuator 205 within the elastic shutter assembly is said to operate between a closed or actuated position and a relaxed position. The designer, however, can choose to place apertures 211 such that shutter assembly 200 is in either the “open” state, i.e. passing light, or in the “closed” state, i.e. blocking light, whenever actuator 205 is in its relaxed position. For illustrative purposes, it is assumed below that elastic shutter assemblies described herein are designed to be open in their relaxed state.

In many cases it is preferable to provide a dual set of “open” and “closed” actuators as part of a shutter assembly so that the control electronics are capable of electrostatically driving the shutters into each of the open and closed states.

Display apparatus 100, in alternative embodiments, includes light modulators other than transverse shutter-based light modulators, such as the shutter assembly 200 described above. For example, FIG. 2B is a cross-sectional view of a rolling actuator shutter-based light modulator 220 suitable for incorporation into an alternative embodiment of the MEMS-based display apparatus 100 of FIG. 1A, according to an illustrative embodiment of the invention. As described further in U.S. Pat. No. 5,233,459, entitled “Electric Display Device,” and U.S. Pat. No. 5,784,189, entitled “Spatial Light Modulator,” the entireties of which are incorporated herein by reference, a rolling actuator-based light modulator includes a moveable electrode disposed opposite a fixed electrode and biased to move in a preferred direction to produce a shutter upon application of an electric field. In one embodiment, the light modulator 220 includes a planar electrode 226 disposed between a substrate 228 and an insulating layer 224 and a moveable electrode 222 having a fixed end 230 attached to the insulating layer 224. In the absence of any applied voltage, a moveable end 232 of the moveable electrode 222 is free to roll towards the fixed end 230 to produce a rolled state. Application of a voltage between the electrodes 222 and 226 causes the moveable electrode 222 to unroll and lie flat against the insulating layer 224, whereby it acts as a shutter that blocks light traveling through the substrate 228. The moveable electrode 222 returns to the rolled state by means of an elastic restoring force after the voltage is removed. The bias towards a rolled state may be achieved by manufacturing the moveable electrode 222 to include an anisotropic stress state.

FIG. 2C is a cross-sectional view of an illustrative non shutter-based MEMS light modulator 250. The light tap modulator 250 is suitable for incorporation into an alternative embodiment of the MEMS-based display apparatus 100 of FIG. 1A, according to an illustrative embodiment of the invention. As described further in U.S. Pat. No. 5,771,321, entitled “Micromechanical Optical Switch and Flat Panel Display,” the entirety of which is incorporated herein by reference, a light tap works according to a principle of frustrated total internal reflection. That is, light 252 is introduced into a light guide 254, in which, without interference, light 252 is for the most part unable to escape the light guide 254 through its front or rear surfaces due to total internal reflection. The light tap 250 includes a tap element 256 that has a sufficiently high index of refraction that, in response to the tap element 256 contacting the light guide 254, light 252 impinging on the surface of the light guide 254 adjacent the tap element 256 escapes the light guide 254 through the tap element 256 towards a viewer, thereby contributing to the formation of an image.

In one embodiment, the tap element 256 is formed as part of beam 258 of flexible, transparent material. Electrodes 260 coat portions of one side of the beam 258. Opposing electrodes 260 are disposed on the light guide 254. By applying a voltage across the electrodes 260, the position of the tap element 256 relative to the light guide 254 can be controlled to selectively extract light 252 from the light guide 254.

The roller-based light modulator 220, and light tap modulator 250 are not the only examples of MEMS light modulators suitable for inclusion in various embodiments of the invention. It will be understood that other MEMS light modulators can exist and can be usefully incorporated into the invention.

U.S. patent application Ser. Nos. 11/251,035 and 11/326,696 have described a variety of methods by which an array of shutters can be controlled via a control matrix to produce images, in many cases moving images, with appropriate gray scale. In some cases, control is accomplished by means of a

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passive matrix array of row and column interconnects connected to driver circuits on the periphery of the display. In other cases it is appropriate to include switching and/or data storage elements within each pixel of the array (the so-called active matrix) to improve either the speed, the gray scale and/or the power dissipation performance of the display.

FIG. 3 is a schematic diagram of a control matrix 300 suitable for controlling the light modulators incorporated into the MEMS-based display apparatus 100 of FIG. 1A, according to an illustrative embodiment of the invention. FIG. 4 is a perspective view of an array 320 of shutter-based light modulators connected to the control matrix 300 of FIG. 3, according to an illustrative embodiment of the invention. The control matrix 300 may address an array of pixels 320 (the "array 320"). Each pixel 301 includes an elastic shutter assembly 302, such as the shutter assembly 200 of FIG. 2A, controlled by an actuator 303. Each pixel also includes an aperture layer 322 that includes apertures 324. Further electrical and mechanical descriptions of shutter assemblies such as shutter assembly 302, and variations thereon, can be found in U.S. patent application Ser. Nos. 11/251,035 and 11/326,696. Descriptions of alternate control matrices can also be found in U.S. patent application Ser. No. 11/607,715.

The control matrix 300 is fabricated as a diffused or thin-film-deposited electrical circuit on the surface of a substrate 304 on which the shutter assemblies 302 are formed. The control matrix 300 includes a scan-line interconnect 306 for each row of pixels 301 in the control matrix 300 and a data-interconnect 308 for each column of pixels 301 in the control matrix 300. Each scan-line interconnect 306 electrically connects a write-enabling voltage source 307 to the pixels 301 in a corresponding row of pixels 301. Each data interconnect 308 electrically connects a data voltage source, ("Vd source") 309 to the pixels 301 in a corresponding column of pixels 301. In control matrix 300, the data voltage  $V_d$  provides the majority of the energy necessary for actuation of the shutter assemblies 302. Thus, the data voltage source 309 also serves as an actuation voltage source.

Referring to FIGS. 3 and 3B, for each pixel 301 or for each shutter assembly 302 in the array of pixels 320, the control matrix 300 includes a transistor 310 and a capacitor 312. The gate of each transistor 310 is electrically connected to the scan-line interconnect 306 of the row in the array 320 in which the pixel 301 is located. The source of each transistor 310 is electrically connected to its corresponding data interconnect 308. The actuators 303 of each shutter assembly 302 include two electrodes. The drain of each transistor 310 is electrically connected in parallel to one electrode of the corresponding capacitor 312 and to one of the electrodes of the corresponding actuator 303. The other electrode of the capacitor 312 and the other electrode of the actuator 303 in shutter assembly 302 are connected to a common or ground potential. In alternate implementations, the transistors 310 can be replaced with semiconductor diodes and or metal-insulator-metal sandwich type switching elements.

In operation, to form an image, the control matrix 300 write-enables each row in the array 320 in a sequence by applying  $V_{we}$  to each scan-line interconnect 306 in turn. For a write-enabled row, the application of  $V_{we}$  to the gates of the transistors 310 of the pixels 301 in the row allows the flow of current through the data interconnects 308 through the transistors 310 to apply a potential to the actuator 303 of the shutter assembly 302. While the row is write-enabled, data voltages  $V_d$  are selectively applied to the data interconnects 308. In implementations providing analog gray scale, the data voltage applied to each data interconnect 308 is varied in relation to the desired brightness of the pixel 301 located at

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the intersection of the write-enabled scan-line interconnect 306 and the data interconnect 308. In implementations providing digital control schemes, the data voltage is selected to be either a relatively low magnitude voltage (i.e., a voltage near ground) or to meet or exceed  $V_{at}$  (the actuation threshold voltage). In response to the application of  $V_{at}$  to a data interconnect 308, the actuator 303 in the corresponding shutter assembly 302 actuates, opening the shutter in that shutter assembly 302. The voltage applied to the data interconnect 308 remains stored in the capacitor 312 of the pixel 301 even after the control matrix 300 ceases to apply  $V_{we}$  to a row. It is not necessary, therefore, to wait and hold the voltage  $V_{we}$  on a row for times long enough for the shutter assembly 302 to actuate; such actuation can proceed after the write-enabling voltage has been removed from the row. The capacitors 312 also function as memory elements within the array 320, storing actuation instructions for periods as long as is necessary for the illumination of an image frame.

The pixels 301 as well as the control matrix 300 of the array 320 are formed on a substrate 304. The array includes an aperture layer 322, disposed on the substrate 304, which includes a set of apertures 324 for respective pixels 301 in the array 320. The apertures 324 are aligned with the shutter assemblies 302 in each pixel. In one implementation the substrate 304 is made of a transparent material, such as glass or plastic. In another implementation the substrate 304 is made of an opaque material, but in which holes are etched to form the apertures 324.

Components of shutter assemblies 302 are processed either at the same time as the control matrix 300 or in subsequent processing steps on the same substrate. The electrical components in control matrix 300 are fabricated using many thin film techniques in common with the manufacture of thin film transistor arrays for liquid crystal displays. Available techniques are described in Den Boer, Active Matrix Liquid Crystal Displays (Elsevier, Amsterdam, 2005), incorporated herein by reference. The shutter assemblies are fabricated using techniques similar to the art of micromachining or from the manufacture of micromechanical (i.e., MEMS) devices. Many applicable thin film MEMS techniques are described in Rai-Choudhury, ed., Handbook of Microlithography, Micromachining & Microfabrication (SPIE Optical Engineering Press, Bellingham, Wash. 1997), incorporated herein by reference. Fabrication techniques specific to MEMS light modulators formed on glass substrates can be found in U.S. patent application Ser. Nos. 11/361,785 and 11/731,628, incorporated herein by reference. For instance, as described in those applications, the shutter assembly 302 can be formed from thin films of amorphous silicon, deposited by a chemical vapor deposition process.

The shutter assembly 302 together with the actuator 303 can be made bi-stable. That is, the shutters can exist in at least two equilibrium positions (e.g. open or closed) with little or no power required to hold them in either position. More particularly, the shutter assembly 302 can be mechanically bi-stable. Once the shutter of the shutter assembly 302 is set in position, no electrical energy or holding voltage is required to maintain that position. The mechanical stresses on the physical elements of the shutter assembly 302 can hold the shutter in place.

The shutter assembly 302 together with the actuator 303 can also be made electrically bi-stable. In an electrically bi-stable shutter assembly, there exists a range of voltages below the actuation voltage of the shutter assembly, which if applied to a closed actuator (with the shutter being either open or closed), holds the actuator closed and the shutter in position, even if an opposing force is exerted on the shutter. The

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opposing force may be exerted by a spring such as spring 207 in shutter-based light modulator 200, or the opposing force may be exerted by an opposing actuator, such as an "open" or "closed" actuator.

The light modulator array 320 is depicted as having a single MEMS light modulator per pixel. Other embodiments are possible in which multiple MEMS light modulators are provided in each pixel, thereby providing the possibility of more than just binary "on" or "off" optical states in each pixel. Certain forms of coded area division gray scale are possible where multiple MEMS light modulators in the pixel are provided, and where apertures 324, which are associated with each of the light modulators, have unequal areas.

In other embodiments the roller-based light modulator 220 or the light tap 250, as well as other MEMS-based light modulators, can be substituted for the shutter assembly 302 within the light modulator array 320.

FIG. 5 is a cross sectional view of a display apparatus 500 incorporating shutter-based light modulators (shutter assemblies) 502, according to an illustrative embodiment of the invention. Each shutter assembly incorporates a shutter 503 and an anchor 505. Not shown are the compliant beam actuators which, when connected between the anchors 505 and the shutters 503, help to suspend the shutters a short distance above the surface. The shutter assemblies 502 are disposed on a transparent substrate 504, preferably made of plastic or glass. A rear-facing reflective layer, reflective film 506, disposed on the substrate 504 defines a plurality of surface apertures 508 located beneath the closed positions of the shutters 503 of the shutter assemblies 502. The reflective film 506 reflects light not passing through the surface apertures 508 back towards the rear of the display apparatus 500. The reflective aperture layer 506 can be a fine-grained metal film without inclusions formed in thin film fashion by a number of vapor deposition techniques including sputtering, evaporation, ion plating, laser ablation, or chemical vapor deposition. In another implementation, the rear-facing reflective layer 506 can be formed from a mirror, such as a dielectric mirror. A dielectric mirror is fabricated as a stack of dielectric thin films which alternate between materials of high and low refractive index. The vertical gap which separates the shutters 503 from the reflective film 506, within which the shutter is free to move, is in the range of 0.5 to 10 microns. The magnitude of the vertical gap is preferably less than the lateral overlap between the edge of shutters 503 and the edge of apertures 508 in the closed state.

The display apparatus 500 includes an optional diffuser 512 and/or an optional brightness enhancing film 514 which separate the substrate 504 from a planar light guide 516. The light guide is comprised of a transparent, i.e. glass or plastic material. The light guide 516 is illuminated by one or more light sources 518, forming a backlight. The light sources 518 can be, for example, and without limitation, incandescent lamps, fluorescent lamps, lasers, or light emitting diodes (LEDs). A reflector 519 helps direct light from lamp 518 towards the light guide 516. A front-facing reflective film 520 is disposed behind the backlight 516, reflecting light towards the shutter assemblies 502. Light rays such as ray 521 from the backlight that do not pass through one of the shutter assemblies 502 will be returned to the backlight and reflected again from the film 520. In this fashion light that fails to leave the display to form an image on the first pass can be recycled and made available for transmission through other open apertures in the array of shutter assemblies 502. Such light recycling has been shown to increase the illumination efficiency of the display.

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The light guide 516 includes a set of geometric light redirectors or prisms 517 which re-direct light from the lamps 518 towards the apertures 508 and hence toward the front of the display. The light re-directors can be molded into the plastic body of light guide 516 with shapes that can be alternately triangular, trapezoidal, or curved in cross section. The density of the prisms 517 generally increases with distance from the lamp 518.

In alternate embodiments the aperture layer 506 can be made of a light absorbing material, and in alternate embodiments the surfaces of shutter 503 can be coated with either a light absorbing or a light reflecting material. In alternate embodiments the aperture layer 506 can be deposited directly on the surface of the light guide 516. In alternate embodiments the aperture layer 506 need not be disposed on the same substrate as the shutters 503 and anchors 505 (see the MEMS-down configuration described below). These and other embodiments for a display illumination system are described in detail in the U.S. patent application Ser. Nos. 11/218,690 and 11/528,191, incorporated herein by reference.

In one implementation the light sources 518 can include lamps of different colors, for instance, the colors red, green, and blue. A color image can be formed by sequentially illuminating images with lamps of different colors at a rate sufficient for the human brain to average the different colored images into a single multi-color image. The various color-specific images are formed using the array of shutter assemblies 502. In another implementation, the light source 518 includes lamps having more than three different colors. For example, the light source 518 may have red, green, blue and white lamps or red, green, blue, and yellow lamps.

A cover plate 522 forms the front of the display apparatus 500. The rear side of the cover plate 522 can be covered with a black matrix 524 to increase contrast. In alternate implementations the cover plate includes color filters, for instance distinct red, green, and blue filters corresponding to different ones of the shutter assemblies 502. The cover plate 522 is supported a predetermined distance away from the shutter assemblies 502 forming a gap 526. The gap 526 is maintained by mechanical supports or spacers 527 and/or by an adhesive seal 528 attaching the cover plate 522 to the substrate 504.

The sealing material 528 can be formed from polymer adhesives such as epoxies, acrylates, or a silicone materials. The adhesive seal 528 should have a curing temperature preferably below about 200° C., it should have a coefficient of thermal expansion preferably below about 50 ppm per degree C. and should be moisture resistant. An exemplary sealant 528 is EPO-TEK B9021-1, sold by Epoxy Technology, Inc. In an alternate embodiment the adhesive is formed from a heat reflowable material such as a solder metal or a glass frit compound.

The adhesive seal 528 seals in a working fluid 530. The working fluid 530 is engineered with viscosities preferably below about 10 centipoise and with relative dielectric constant preferably above about 2.0, and dielectric breakdown strengths above about 10<sup>4</sup> V/cm. The working fluid 530 can also serve as a lubricant. In alternate implementations the working fluid 530 has a refractive index that is either greater than or less than that of the substrate 504. In one implementation the working fluid has a refractive index greater than 2.0. Suitable working fluids 530 include, without limitation, de-ionized water, methanol, ethanol, silicone oils, fluorinated silicone oils, dimethylsiloxane, polydimethylsiloxane, hexamethyldisiloxane, and diethylbenzene.

In another implementation, the working fluid 530 is a hydrophobic liquid with a high surface wetting capability. Preferably, its wetting capabilities are sufficient to wet the



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front as well as the rear surfaces of the shutter assemblies 502. Hydrophobic fluids are capable of displacing water from the surfaces of shutter assemblies 502. In another implementation, the working fluid 530 contains a suspension of particles with diameters in the range of 0.5 to 20 microns. Such particles scatter light to increase the viewing angle of a display. In another implementation the working fluid 530 contains dye molecules in solution for absorbing some or all frequencies of visible light to increase the contrast of the display.

A sheet metal or molded plastic assembly bracket 532 holds the cover plate 522, the substrate 504, the backlight 516 and the other component parts together around the edges. The assembly bracket 532 is fastened with screws or indent tabs to add rigidity to the combined display apparatus 500. In some implementations, the light source 518 is molded in place by an epoxy potting compound. Reflectors 536 help return light escaping from the edges of light guide 516 back into the light guide. Not shown in FIG. 5 are electrical interconnects which provide control signals as well as power to the shutter assemblies 502 and the lamps 518.

Further details and alternate configurations for the display apparatus 500, including manufacturing methods therefore, can be found in the U.S. patent application Ser. Nos. 11/361,785 and 11/731,628, incorporated herein by reference.

Display apparatus 500 is referred to as the MEMS-up configuration, wherein the MEMS based light modulators are formed on a front surface of substrate 504, i.e. the surface that faces toward the viewer. The shutter assemblies 502 are built directly on top of the reflective aperture layer 506. In an alternate embodiment of the invention, referred to as the MEMS-down configuration, the shutter assemblies are disposed on a substrate separate from the substrate on which the reflective aperture layer is formed. The substrate on which the reflective aperture layer is formed, defining a plurality of apertures, is referred to herein as the aperture plate. In the MEMS-down configuration, the substrate that carries the MEMS-based light modulators takes the place of the cover plate 522 in display apparatus 500 and is oriented such that the MEMS-based light modulators are positioned on the rear surface of the top substrate, i.e. the surface that faces away from the viewer and toward the back light 516. The MEMS-based light modulators are thereby positioned directly opposite to and across a gap from the reflective aperture layer. The gap can be maintained by a series of spacer posts connecting the aperture plate and the substrate on which the MEMS modulators are formed. In some implementations the spacers are disposed within or between each pixel in the array. The gap or distance that separates the MEMS light modulators from their corresponding apertures is preferably less than 10 microns, or a distance that is less than the overlap between shutters and apertures.

Further details and alternate embodiments for the MEMS-down display configuration can be found in the U.S. patent application Ser. Nos. 11/361,785 and 11/528,191 referenced above.

In other embodiments, the roller-based light modulator 220 or the light tap 250, as well as other MEMS-based light modulators, can be substituted for the shutter assemblies 502 within the display assembly 500.

FIGS. 6A and 6B illustrate an alternative shutter-based light modulator (shutter assembly) 2200 suitable for inclusion in various embodiments of the invention. The light modulator 2200 is an example of a dual actuator shutter assembly, and is shown in FIG. 6A in an open state. FIG. 6B is a view of the dual actuator shutter assembly 2200 in a closed state. Shutter assembly 2200 is described in further detail in U.S. patent application Ser. No. 11/251,035, refer-

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enced above. In contrast to the shutter assembly 200, shutter assembly 2200 includes actuators 2208 and 2210 on either side of a shutter 2202. Each actuator 2210 and 2208 is independently controlled. A first actuator, a shutter-open actuator 2210, serves to open the shutter 2202. A second opposing actuator, the shutter-close actuator 2208, serves to close the shutter 2202. Both actuators 2210 and 2208 are compliant beam electrode actuators. The actuators 2210 and 2208 open and close the shutter 2202 by driving the shutter 2202 substantially in a plane parallel to an aperture layer 2204 over which the shutter is suspended. The shutter 2202 is suspended a short distance over the aperture layer 2204 by anchors 2206 attached to the actuators 2210 and 2208. The inclusion of supports attached to both ends of the shutter 2202 along its axis of movement reduces out of plane motion of the shutter 2202 and confines the motion substantially to a plane parallel to the substrate. By analogy to the control matrix 300 of FIG. 3, a control matrix suitable for use with shutter assembly 2200 might include one transistor and one capacitor for each of the opposing shutter-open and shutter-close actuators 2210 and 2208.

The shutter 2202 includes three shutter apertures 2212, through which light can pass. The remainder of the shutter 2202 obstructs the passage of light. In various embodiments, the side of the shutter 2202 facing the reflective aperture layer 2204 is coated with a light absorbing material or a reflective material to absorb or reflect, respectively, obstructed light.

The reflective aperture layer 2204 is deposited on a transparent substrate, preferably formed from plastic or glass. The reflective aperture layer 2204 can be formed from a film of metal deposited on the substrate, a dielectric mirror, or other highly reflective material or combination of materials. The reflective aperture layer 2204 has a set of apertures 2214 formed in it to allow light to pass through the apertures, from the transparent substrate, towards the shutter 2202. The reflective aperture layer 2204 has one aperture corresponding to each shutter aperture 2212. For example, for an array of light modulators including shutter assemblies 2200, the reflective aperture layer includes three apertures 2214 for each shutter assembly 2200. Each aperture has at least one edge around its periphery. For example, the rectangular apertures 2214 have four edges. In alternative implementations in which circular, elliptical, oval, or other curved apertures are formed in the reflective aperture layer 2204, each aperture may have only a single edge. In other embodiments the apertures need not be separated or disjoint in the mathematical sense, but instead can be connected. That is to say, while portions or shaped sections of the aperture may have a correspondence to each shutter, several of these sections may be connected such that a single continuous perimeter of the aperture is shared by multiple shutters.

In FIG. 6A, the shutter assembly 2200 is in an open state. Actuator 2208 is in an open position, and actuator 2210 is in a collapsed position. Apertures 2214 are visible through the shutter apertures 2212. As visible, the shutter apertures 2212 are larger in area than the apertures 2214 formed in the reflective aperture layer 2204. The size differential increases the range of angles at which light can pass through the shutter apertures 2212 towards an intended viewer.

In various embodiments, it is advantageous for the shutters used in shutter assemblies to overlap the apertures to which they correspond, when the shutters are in the closed position.

In FIG. 6B, the shutter assembly is a closed state. Actuator 2208 is in a collapsed position and actuator 2210 is in an open position. Light blocking portions of the shutter 2202 cover the apertures 2214 in the reflective aperture layer 2204. The light blocking portions of the shutter 2202 overlap the edges of the



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apertures **2214** in the reflective aperture layer **2204** by a predefined overlap **2216**. In some implementations, even when a shutter is in a closed state, some light, at angles far from an axis normal to the shutter **2202**, may leak through the apertures **2214**. The overlap included in shutter assembly **2200** reduces or eliminates this light leakage. While, as depicted in FIG. 6B, the light blocking portions of shutter **2202** overlap all four edges of the aperture, having the light blocking portions of shutter **2202** overlap even one of the edges reduces light leakage.

FIGS. 7A-7C are cross-sectional views of various configurations of the shutter assembly **2200** in relation to the transparent substrate on which the reflective aperture layer **2204** is formed. The cross sectional views correspond to the line labeled B-B' on FIGS. 6A and 6B. For purposes of illustration, the shutter **2202** is illustrated in FIGS. 7A-7C as having only a single shutter aperture **2323** and two light blocking portions **2324**.

FIG. 7A is a cross section of a first configuration of a display apparatus **2300** including a shutter assembly **2301** similar to that depicted in FIG. 6 in the closed state taken across line B-B', according to an illustrative embodiment of the invention. In the first configuration, the shutter assembly **2301** is formed on a reflective aperture layer **2302**. The reflective aperture layer **2302** is formed from a thin metal film deposited on a transparent substrate **2304**. Alternately, the reflective aperture layer **2302** can be formed from a dielectric mirror, or other highly reflective material or combination of materials. The reflective aperture layer **2302** is patterned to form apertures **2306**. The transparent substrate **2304** is positioned proximate a light guide **2308**. The transparent substrate **2304** and the light guide **2308** are separated by a gap **2309** filled with a fluid, such as air. The refractive index of the fluid is preferably less than that of the light guide **2308**. Suitable light guides **2308** for display apparatus **2300** are described further in U.S. patent application Ser. No. 11/528,191, the entirety of which is herein incorporated by reference. The display apparatus **2300** also includes a front-facing rear reflective layer **2310** positioned adjacent the rear side of the light guide **2308**.

The shutter assembly **2301** includes the shutter **2314** supported proximate to the reflective aperture layer **2302** by anchors **2316** via portions of opposing actuators **2318** and **2320**. The anchors **2316** and actuators **2318** and **2320** suspend the shutter **2314** at about a constant distance **H1** (measured from the bottom of the shutter **2314**) over the reflective aperture layer **2302**. In addition, the display apparatus **2300** includes a cover plate **2314** supported over the transparent substrate **2304** by spacer posts **2312**. The spacer posts **2312** keep the cover plate at about a second constant distance **H2** away from the top of the shutter **2314**. The substrates **2304** and **2311** can be made of a substantially rigid material, such as glass, in which case a relatively low density of spacers **2312** may be used to maintain the desired spacing **H2**. For example, with rigid substrates, the display apparatus **2300**, in one implementation, includes one spacer **2312** for every 4 pixels, though other densities, both higher and lower, may also be employed. In an alternative implementation either substrate **2304** or **2311** can be made of a flexible material, such as plastic, in which case it is preferable to have a higher density of spacers **2312**, for example, one spacer **2312** within or between each pixel in the array.

The gap between the cover plate **2311** and the transparent substrate **2304** is filled with a working fluid **2322**, such as working fluid **530**, described above. The working fluid **2322** preferably has a refractive index greater than that of the transparent substrate **2304**. In another implementation the work-

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ing fluid has a refractive index greater than 2.0. In another implementation the working fluid **2322** has a refractive index that is equal to or less than the index of refraction of the transparent substrate **2304**.

As indicated above, the shutter assembly **2301** is in the closed state. Light blocking portions **2324** of the shutter **2314** overlap the edges of the apertures **2306** formed in the reflective aperture layer **2302**. The light blocking properties of shutter **2314** are improved when the gap between the shutter and the aperture, i.e. the distance **H1**, is made as small as possible. In one implementation, **H1** is less than about 100  $\mu\text{m}$ . In another implementation, **H1** is less than about 10  $\mu\text{m}$ . In still another implementation, **H1** is about 1  $\mu\text{m}$ . In an alternative embodiment the distance **H1** is greater than 0.5 mm, but remains smaller than the display pitch. The display pitch is defined as the distance between pixels (measured center to center), and in many cases is established as the distance between apertures, such as apertures **2306**, measured center to center, in the rear-facing reflective layer **2302**.

The size of the overlap **W1** is preferably proportional to the distance **H1**. While the overlap **W1** may be smaller, preferably the overlap **W1** is greater than or equal to the distance **H1**. In one implementation the overlap **W1** is greater than or equal to 1 micron. In another implementation the overlap **W1** is between about 1 micron and 10 microns. In another implementation the overlap **W1** is greater than 10 microns. In one particular implementation, the shutter **2314** is about 4  $\mu\text{m}$  thick. **H1** is about 2  $\mu\text{m}$ , **H2** is about 2  $\mu\text{m}$ , and **W1**  $\geq$  2  $\mu\text{m}$ . By having the overlap **W1** being greater than or equal to **H1**, if the shutter assembly **2301** is in the closed state as depicted in FIG. 7A, most light having a sufficient angle to escape the light guide **2308** through the apertures **2306** impacts the light blocking portions **2324** of the shutter **2314**, thereby improving the contrast ratio of the display apparatus **2300**.

**H2** is preferably about the same distance as **H1**. The spacer posts **2312** are preferably formed from a polymer material that is lithographically patterned, developed, and/or etched into cylindrical shapes. The height of the spacer is determined by the cured thickness of the polymer material. Methods and materials for formation of spacers **2312** are disclosed in co-owned U.S. patent application Ser. No. 11/361,785, filed Feb. 23, 2006, incorporated herein by reference. In an alternative embodiment the spacer **2312** can be formed from a metal which is electrochemically deposited into a mold made from a sacrificial material.

FIG. 7B is a cross section of a second configuration of a display apparatus **2340** including a shutter assembly **2341** similar to that depicted in FIG. 6 in the closed state, according to an illustrative embodiment of the invention. This second configuration is referred to as the MEMS-down configuration, in which the reflective aperture layer **2344** is formed on a transparent substrate called the aperture plate **2346**, which is distinct from the light modulator substrate **2342** to which shutter assembly **2341** is anchored. The shutter assembly includes a shutter **2354** having light blocking portions **2362** and shutter apertures **2363** formed therein. Like the aperture plate **2346**, the light modulator substrate **2342** is also transparent. The two substrates **2342** and **2346** are separated by a gap. The two substrates **2342** and **2346** are aligned during assembly such that a one to one correspondence exists, as indicated in FIG. 6, between each of the apertures **2347** and the light blocking portions **2362** of shutter **2354** when that shutter is in the closed position, and/or between the apertures **2347** and the shutter apertures **2363** when that shutter is in the open position. In alternative embodiments, the correspondence between apertures and either light blocking portions

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2362 or shutter apertures 2363 of a shutter 2354 is a one to many or many to one correspondence.

In the MEMS-down display apparatus 2340, the shutter assembly 2341 is formed on the rear-facing surface of the light modulator substrate 2342, i.e. on the side which faces the light guide 2348. In display apparatus 2340, the aperture plate 2346 is positioned between the light modulator substrate 2342 and the light guide 2348. The reflective aperture layer 2344 is formed from a thin metal film deposited on the front-facing surface of transparent aperture plate 2346. The reflective aperture layer 2344 is patterned to form apertures 2347. In another implementation, the reflective layer 2344 can be formed from a mirror, such as a dielectric mirror. A dielectric mirror is fabricated from a stack of dielectric thin films with different refractive indices, or from combinations of metal layers and dielectric layers.

The aperture plate 2346 is positioned proximate to a backlight or light guide 2348. The aperture plate 2346 is separated from the light guide 2348 by a gap 2349 filled with a fluid, such as air. The refractive index of the fluid is preferably less than that of the light guide 2348. Suitable backlights 2348 for display apparatus 2340 are described further in U.S. patent application Ser. No. 11/528,191, the entirety of which is herein incorporated by reference. The display apparatus 2340 also includes a front-facing rear reflective layer 2350 positioned adjacent the rear side of the backlight 2348. The front-facing reflective layer 2350 combined with the rear-facing reflective layer 2344 forms an optical cavity which promotes recycling of light rays which do not initially pass through apertures 2347. The shutter assembly 2341 includes the shutter 2354 supported proximate to the transparent substrate 2342 by anchors 2356 via portions of opposing actuators 2358 and 2360. The anchors 2356 and actuators 2358 and 2360 suspend the shutter 2354 at about a constant distance H4 (measured from the top of the shutter 2354) below the light modulator substrate 2342. In addition, display apparatus includes spacer posts 2357, which support the light modulator substrate 2342 over the aperture plate 2346. The spacer posts 2357 keep the light modulator substrate 2342 at about a second constant distance H5 away from the aperture plate 2346, thereby keeping the bottom surface of shutter 2354 at a third about constant distance H6 above the reflective aperture layer 2344. The spacer posts 2357 are formed in a fashion similar to those of spacers 2312.

The gap between the light modulator substrate 2342 and the aperture plate 2346 is filled with a working fluid 2352, such as working fluid 530, described above. The working fluid 2352 preferably has a refractive index greater than that of the transparent aperture plate 2346. In another implementation the working fluid has a refractive index greater than 2.0. In another implementation the working fluid 2352 preferably has a refractive index that is equal to or less than the index of refraction of the aperture plate 2346.

As indicated above, the shutter assembly 2341 is in the closed state. Light blocking portions 2362 of the shutter 2354 overlap the edges of the apertures 2347 formed in the reflective aperture layer 2344. The size of the overlap W2 is preferably proportional to the distance H6. While the overlap W2 may be smaller, preferably the overlap W2 is greater than or equal to the distance H6. In one implementation, H6 is less than about 100  $\mu\text{m}$ . In another implementation, H6 is less than about 1  $\mu\text{m}$ . In still another implementation, H6 is about 1  $\mu\text{m}$ . In an alternative embodiment the distance H6 is greater than 0.5 mm, but remains smaller than the display pitch. The display pitch is defined as the distance between pixels (measured center to center), and in many cases is established as the distance between the centers of apertures in the rear-facing

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reflective layer, such as apertures 2347. H4 is preferably about the same distance as H6. In one particular implementation, the shutter 2354 is about 4  $\mu\text{m}$  thick, H6 is about 2  $\mu\text{m}$ , H4 is about 2  $\mu\text{m}$ , H5 is about 8  $\mu\text{m}$  and  $W2 \geq 2 \mu\text{m}$ . By having the overlap W2 being greater than or equal to H6, if the shutter assembly 2341 is in the closed state as depicted in FIG. 7B, most light having a sufficient angle to escape the backlight 2348 through the apertures 2347 impacts the light blocking portions 2362 of the shutter 2354, thereby improving the contrast ratio of the display apparatus 2340.

FIG. 7C is a cross section of a third configuration of a display apparatus 2370 including a shutter assembly 2371 similar to that depicted in FIG. 6 in the closed state, according to an illustrative embodiment of the invention. In comparison to the second configuration of the display apparatus 2340 described above, the display apparatus 2370 is designed to account for minor misalignments that may occur during the aligning and bonding of a light modulator substrate 2372 (similar to light modulator substrate 2342) on which a shutter assembly 2371 is formed to an aperture plate 2374 (similar to the aperture plate 2346) on which a reflective aperture layer 2376 is deposited. To address this potential issue, the display apparatus 2370 includes an additional layer of light absorbing material 2377, deposited on the light modulator substrate 2372. The light absorbing material 2377 may be part of a black mask, though at least some of the light absorbing material 2377 is preferably located in the interior of a pixel to which the shutter assembly 2371 corresponds. The light absorbing material 2377 absorbs light 2378 that would otherwise pass through the light modulator substrate 2372 while the shutter 2382 is in the closed state. Additional light absorbing material 2377 may be deposited on the front side of reflective aperture layer 2376 to absorb light, for example light 2380 deflected from a shutter 2382.

FIG. 7D is a cross section of a fourth configuration of a display apparatus 2390 including a shutter assembly 2385 similar to that depicted in FIG. 6 in the closed state, according to an illustrative embodiment of the invention. In comparison to the second configuration of shutter assembly 2354 described above, the shutter assembly 2385 is fabricated according to a different process resulting in different cross sectional thicknesses for some of its members. The resulting shutter 2393 is referred to herein as a corrugated shutter. The design guidelines for gap distances, e.g. H8 and H10, and for the overlap parameter W4, however, are preferably unchanged from the corresponding gap distances and the overlap parameters described above. The display apparatus 2390 includes a transparent light modulator substrate 2386, oriented in the MEMS down configuration, and to which the shutter assembly 2385 is attached. The display apparatus 2390 also includes a transparent aperture plate 2387 on which a rear-facing reflective aperture layer 2388 is deposited. The display apparatus 2390 includes a fluid 2389 which fills the gap between substrates 2386 and 2387. The fluid 2389 preferably has a refractive index higher than that of the aperture plate 2387. The display apparatus also includes a backlight 2348 along with front-facing reflective layer 2350.

The shutter assembly 2385 is in the closed state. Light blocking portions 2391 of the corrugated shutter 2393 overlap the edges of apertures 2394 formed in the reflective aperture layer 2388. The corrugated shutter 2393 is comprised of two connected flat plate sections: section 2391 which is oriented horizontally and section 2392 which is oriented vertically. Each flat plate 2391 and 2392 is comprised of thin film materials with thicknesses in the range of 0.2 to 2.0  $\mu\text{m}$ . In a particular embodiment the thickness of the horizontal section 2391 is 0.5  $\mu\text{m}$ . The vertical section 2392 provides a stiffness

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to the corrugated shutter **2393** and a height which matches that of actuator **2358** without requiring the deposition of a bulk materials thicker than about 2  $\mu\text{m}$ . Methods and materials for formation of shutters with a corrugated and/or three dimensional structures are disclosed in co-owned U.S. patent application Ser. No. 11/361,785, filed Feb. 23, 2006, incorporated herein by reference.

Similar to dimensions described for display apparatus **2340**, in a particular example the dimensions of **H8**, **H9**, and **H10** of display apparatus **2390** can be 2, 8, and 2  $\mu\text{m}$  respectively. The overlap **W4** is preferably greater than or equal to the distance **H10**. In another example, the distance **H10** and the overlap **W4** can be  $\geq 1$   $\mu\text{m}$ . Using the materials and methods for a corrugated shutter **2393**, however, the thickness of section **2391** can be as thin as 0.5  $\mu\text{m}$ . By having the overlap **W4** greater than or equal to **H10**, if the shutter assembly **2385** is in the closed state as depicted in FIG. 7A, most light having a sufficient angle to escape the backlight **2348** through the apertures **2394** impacts the light blocking portions **2391** of the shutter **2393**, thereby improving the contrast ratio of the display apparatus **2390**.

FIG. 8 is a cross sectional view of a first electrowetting-based light modulation array **2400**, according to an illustrative embodiment of the invention. The light modulation array **2400** includes a plurality of electrowetting-based light modulation cells **2402a-2402d** (generally "cells **2402**") formed on an optical cavity **2404**. The light modulation array **2400** also includes a set of color filters **2406** corresponding to the cells **2402**.

Each cell **2402** includes a layer of water (or other transparent conductive or polar fluid) **2408**, a layer of light absorbing oil **2410**, a transparent electrode **2412** (made, for example, from indium-tin oxide) and an insulating layer **2414** positioned between the layer of light absorbing oil **2410** and the transparent electrode **2412**. Illustrative implementation of such cells are described further in U.S. Patent Application Publication No. 2005/0104804, published May 19, 2005 and entitled "Display Device," incorporated herein by reference. In the embodiment described herein, the transparent electrode **2412** takes up only a portion of a rear surface of a cell **2402**.

The remainder of the rear surface of a cell **2402** is formed from a reflective aperture layer **2416** that forms the front surface of the optical cavity **2404**. The rear-facing reflective layer **2416** is patterned to form apertures, which in the embodiment of cell **2402** are coincident with the transparent electrode **2412**. Preferably, when in the closed position, the layer of light absorbing oil **2410** overlaps one or more edges of its corresponding aperture in the reflective aperture layer **2416**. The reflective aperture layer **2416** is formed from a reflective material, such as a reflective metal or a stack of thin films forming a dielectric mirror. For each cell **2402**, an aperture is formed in the reflective aperture layer **2416** to allow light to pass through. In an alternate embodiment, the electrode **2412** for the cell is deposited in the aperture and over the material forming the reflective aperture layer **2416**, separated by another dielectric layer.

The remainder of the optical cavity **2404** includes a light guide **2418** positioned proximate the reflective aperture layer **2416**, and a second reflective layer **2420** on a side of the light guide **2418** opposite the reflective aperture layer **2416**. A series of light redirectors **2421** are formed on the rear surface of the light guide, proximate the second reflective layer. The light redirectors **2421** may be either diffuse or specular reflectors. One of more light sources **2422** inject light **2424** into the light guide **2418**.

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In an alternate implementation the light sources **2422** can include lamps of different colors, for instance, the colors red, green, and blue. A color image can be formed by sequentially illuminating images with lamps of different colors at a rate sufficient for the human brain to average the different colored images into a single multi-color image. The various color-specific images are formed using the array of electrowetting modulation cells **2402**. In another implementation, the light source **2422** includes lamps having more than three different colors. For example, the light source **2422** may have red, green, blue and white lamps or red, green, blue, and yellow lamps.

In an alternative implementation, the cells **2402** and the reflective aperture layer **2416** are formed on an additional light modulator substrate which is distinct from light guide **2418** and separated from it by a gap. (See for example the light modulator substrate **2513** of FIG. 9.) In yet another implementation, a layer of material with a refractive index less than that of the light guide **2418** is interposed between the reflective aperture layer **2416** and the light guide **2418**. The layer of material with lower refractive index may help to improve the uniformity of light emitted from the light guide **2418**.

In operation, application of a voltage to the electrode **2412** of a cell (for example, cell **2402b** or **2402c**) causes the light absorbing oil **2410** in the cell to collect in one portion of the cell **2402**. As a result, the light absorbing oil **2410** no longer obstructs the passage of light through the aperture formed in the reflective aperture layer **2416** (see, for example, cells **2402b** and **2402c**). Light escaping the backlight at the aperture is then able to escape through the cell and through a corresponding color (for example, red, green, or blue) filter in the set of color filters **2406** to form a color pixel in an image. When the electrode **2412** is grounded, the light absorbing oil **2410** covers the aperture in the reflective aperture layer **2416**, absorbing any light **2424** attempting to pass through it (see for example cell **2402a**).

The area under which oil **2410** collects when a voltage is applied to the cell **2402** constitutes wasted space in relation to forming an image. This area cannot pass light through, whether a voltage is applied or not, and therefore, without the inclusion of the reflective portions of reflective apertures layer **2416**, would absorb light that otherwise could be used to contribute to the formation of an image. However, with the inclusion of the reflective aperture layer **2416**, this light, which otherwise would have been absorbed, is reflected back into the light guide **2420** for future escape through a different aperture.

FIG. 9 is a cross sectional view of a second electrowetting-based light modulation array **2500**, according to an illustrative embodiment of the invention. The second electrowetting-based light modulation array **2500** includes three sub-arrays **2501a**, **2501b**, and **2501c** of colored electrowetting-based light modulation cells **2502** (generally "cells **2502**"), positioned on top of one another. Each cell **2502** includes a transparent electrode **2504**, and a colored oil **2506** separated by an insulator **2508**. In one implementation, the oil **2506** in the cells **2502** of sub-array **2501a** is colored cyan, the oil **2506** in the cells **2502** of sub-array **2501b** is colored yellow, and the oil **2506** in the cells **2502** of sub-array **2501c** is colored magenta. The cells **2502** in sub-array **2501a** and the cells **2502** of sub-array **2501b** share a common layer of water **2520**. The cells **2502** of sub-array **2501c** include their own layer of water **2520**.

The electrowetting-based light modulation array **2500** includes a light-recycling optical cavity **2510** coupled to the three sub-arrays **2501a-2501c**. The optical cavity **2510**

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includes a light guide **2512** and a light modulator substrate **2513**, separated from the light guide **2512** by a gap **2515**. The front surface of the light modulator substrate **2513** includes a rear-facing reflective aperture layer **2514**. The reflective aperture layer **2514** is formed from a layer of metal or a stack of thin films forming a dielectric mirror. Apertures **2516** are patterned into the reflective aperture layer beneath the cells **2502** of the sub-arrays **2501a-2501c** to allow light to escape the light guide and pass through the sub-arrays **2501a-2501c** to form an image. The transparent electrodes **2504** of cells **2502** are formed over the top of the reflective aperture layer **2514**.

The substrates, i.e., light guide **2512** and modulator substrate **2513**, are separated by a gap **2515** filled with a fluid, such as air. The refractive index of the fluid is less than that of the light guide **2512**. A front-facing reflective layer **2518** is formed on, or positioned proximate to, the opposite side of the light guide **2512**. The light modulation array **2500** includes at least one light source **2522** for injecting light into the light guide **2512**. Suitable light guides **2618** for display apparatus **2600** are described further in U.S. patent application Ser. No. 11/528,191, the entirety of which is herein incorporated by reference.

FIG. **10** is a cross sectional view of a third electrowetting-based light modulation array **2600**, according to an illustrative embodiment of the invention. The light modulation array **2600** includes a plurality of electrowetting-based light modulation cells **2602a-2602c** (generally “cells **2602**”) formed on an optical cavity **2604**. The light modulation array **2600** also includes a set of color filters **2606** corresponding to the cells **2602**.

While the array **2400** might be considered an example of an array in a MEMS-up configuration, the array **2600** is an example of an electrowetting-based array assembled in a MEMS-down configuration. Each cell **2602** includes a layer of water (or other transparent conductive or polar fluid) **2608**, a layer of light absorbing oil **2610**, a transparent electrode **2612** (made, for example, from indium-tin oxide) and an insulating layer **2614** positioned between the layer of light absorbing oil **2610** and the transparent electrode **2612**. In the MEMS-down configuration of light modulator array **2600**, however, both the insulating layer **2614** and the transparent electrode **2612** are disposed on a light modulator substrate **2630** distinct from an aperture plate **2632**. Like the light modulator substrate **2630**, the aperture plate **2632** is also a transparent substrate. The light modulator substrate **2630** is the topmost substrate and is oriented such that control electrodes such as transparent electrode **2612** are disposed on the rear surface of substrate **2630**, i.e. the surface that faces away from the viewer and toward the light guide. In addition to transparent electrode **2612**, the rear surface of light modulator substrate **2630** can carry other common components of a switching or control matrix for the modulator array, including without limitation, row electrodes, column electrodes, transistors for each pixel and capacitors for each pixel. The electrodes and switching components formed on light modulator substrate **2630**, which govern the actuation of light modulators in the array, are disposed opposite to and across a gap **2636** from a reflective aperture layer **2616**, disposed on the front surface of aperture plate **2632**. The gap **2636** is filled with the electrowetting fluid components water **2608** and oil **2610**.

The reflective aperture layer **2616** is deposited on transparent substrate **2632**, preferably formed from plastic or glass. The reflective aperture layer **2616** can be formed from a film of metal deposited on the substrate, a dielectric mirror, or other highly reflective material or combination of materials.

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The reflective aperture layer **2616** is a rear-facing reflective layer, forming the front surface of optical cavity **2604**. The reflective aperture layer **2616** has a set of apertures **2617** formed in it to allow light to pass through the apertures toward the electrowetting fluid components **2608** and **2610**. Optionally, the aperture plate **2632** includes a set of color filters **2606** deposited on the top surface of reflective aperture **2616** and filling the apertures **2617**.

The aperture plate **2632** is positioned between the light modulator substrate **2630** and the light guide **2618**. The substrates **2632** and **2618** are separated from each other by a gap **2634** filled with a fluid (such as air). The refractive index of the fluid is less than that of the light guide **2618**. Suitable light guides **2618** for display apparatus **2600** are described further in U.S. patent application Ser. No. 11/528,191, the entirety of which is herein incorporated by reference. The optical cavity **2604** also includes substrates **2632**, **2618**, and the front-facing rear reflective layer **2620** positioned adjacent the rear side of the light guide **2618**. One or more light sources **2622** inject light into the light guide **2618**.

The reflective aperture layer **2616** has one aperture **2617** corresponding to each light modulator cell **2602** in the array **2600**. Similarly, the light modulator substrate **2630** has one transparent electrode **2612** or one set of pixel transistors and capacitors for each light modulator cell **2602**. The substrates **2630** and **2632** are aligned during assembly to ensure that corresponding apertures **2617** are positioned where light will not be obstructed by the oil **2610** when cells are actuated or held in the open state, e.g. cell **2602b**.

Fabrication of an Aperture Plate

The aperture plate **2700** of FIG. **11** illustrates the detailed structures within one implementation of an aperture plate, such as aperture plate **2346**, **2374**, **2387**, or **2632** according to an illustrative embodiment of the invention. The aperture plate **2700** includes a substrate **2702**, a dielectrically enhanced metal mirror **2704**, a light absorbing layer **2706**, and a spacer post **2708**. The dielectrically enhanced metal mirror and the light absorbing layer have been patterned into apertures **2709**.

The substrate **2702** is preferably a transparent material, for example glass or plastic. The dielectrically enhanced metal mirror **2704** is comprised of a 5-layer stack of materials including, in order from the substrate up, a thin film of  $\text{Si}_3\text{N}_4$  **2710**, a thin film of  $\text{SiO}_2$  **2712**, another thin film of  $\text{Si}_3\text{N}_4$  **2710**, another thin film of  $\text{SiO}_2$ , **2712**, and a thin film of aluminum **2714**. The relative thicknesses and preferred refractive indices of these layers are given in Table 1:

TABLE 1

Film Thicknesses and Refractive Indices for a Dielectrically Enhanced Metal Mirror.		
Thin film material	Thickness	Refractive index
5. Aluminum	200 nm or less	NA
4. $\text{SiO}_2$	88 nm	1.46
3. $\text{Si}_3\text{N}_4$	64 nm	2.0
2. $\text{SiO}_2$	88 nm	1.46
1. $\text{Si}_3\text{N}_4$	64 nm	2.0

The light absorbing layer **2706** can be formed from a thin film of black chrome, which is a composite of chromium metal particles suspended in an oxide or nitride matrix. Examples include Cr particles in a  $\text{Cr}_2\text{O}_3$  matrix or Cr particles in an  $\text{SiO}_2$  matrix. In other implementations black chrome can be formed from a thin metal film of chromium

upon which a thin film of CrOx (a sub-oxide of chromium) has been either grown or deposited. A preferred thickness for the black chrome is 150 nm.

The aperture windows 2709 can be patterned from the thin film stack of materials 2704 and 2706 by processes known in the art such as photolithography and etch or by photolithography and lift-off. In the etch process a layer of photoresist is added to the top of the thin film stack and then exposed to UV light through a mask. After developing the aperture pattern in the exposed layer of photoresist, the whole stack is etched in the region of apertures 2709 down to the substrate 2702. Such etching may be accomplished by immersion in wet chemicals, by a dry plasma or ion beam etch, or any combination of the above. In the lift-off process the layer of photoresist is added to the glass before deposition of the thin film stack, the resist being developed into a pattern that is a reverse of the etch mask pattern. The thin film stack is then deposited over the top of the photoresist, such that the thin film stack makes contact to the glass everywhere except in the regions of the apertures 2709. After deposition of the thin film stack is complete, the substrate is dipped into a bath of chemicals that dissolves or lifts-off the photoresist as well as any thin film materials that were deposited on top of the photoresist.

The spacer post 2708 is formed from a photo-imageable polymer such as such as a photo-imageable epoxy (in particular a novolac epoxy) or a photo-imageable polyimide material. Other polymer families that can be prepared in photo-imageable form and are useful for this application include polyarylene, parylene, benzocyclobutane, perfluorocyclobutane, silsequioxane, and silicone polymers. A particular photo-imageable resist useful for the spacer application is the Nano SU-8 material available from Microchem Corporation, headquartered in Newton, Mass.

The polymer spacer material is initially deposited as a thick film on top of the thin film stack 2704 and 2706 after the apertures 2709 have been patterned. The photo-imageable polymer is then exposed to UV light through a mask. Alignment marks help to ensure that the resultant spacers 2708 are located correctly with respect to apertures 2709. For instance, alignment fiducials can be formed on the periphery of the display during the process of etching the apertures 2709. These fiducials are then aligned to a corresponding set of fiducials on the exposure mask to ensure a correct location of spacers 2708. A developing process is then effective at removing all of the polymer except where it was exposed to the UV light. In an alternate method, the features on the exposure mask may be aligned directly to display features on the substrate 2702, such as the apertures 2709.

In the particular implementation described with respect to display apparatus 2340, the spacer posts can be 8 microns tall. In other implementations spacer heights may range from about 2 microns to about 50 microns. When cross sectioned in the plane of the substrate 2702, the spacers may take regular shapes such as a cylinder or a rectangle with widths in the range of 2 to 50 microns. Alternately, they can have complex irregular cross sections which are designed to maximize the contact area of the spacer while fitting between other structures on the substrate, such as apertures 2709. In a preferred implementation the spacer size, shape and placement is determined so that the spacers do not interfere with the movement of the shutters, such as shutters 2354 or other MEMS components, such as actuators 2358 in display apparatus 2340.

In another embodiment, the spacer post 2708 is not provided as a polymer material but is instead composed of a heat reflowable joining material, such as a solder alloy. Exemplary heat reflowable materials are described below with respect to FIG. 13B. The solder alloy can pass through a melting or

reflow step which allows the solder alloy to wet or bond to a mating surface on the opposing substrate. The solder alloy therefore performs an additional function as a joining material between an aperture plate, such as aperture plate 2346 and a modulator substrate, such as substrate 2342. Because of the reflow process, the solder alloy typically relaxes to an oblate shape referred to as the solder bump. A predetermined spacing between substrates can be maintained through control over the average volume of material in the solder bump. Solder bumps can be applied to aperture plate 2700 by means of thin film deposition, by thick film deposition through a stencil mask, or by electroplating.

In another embodiment, the aperture plate 2700 can be subjected to a sandblasting treatment after the steps of forming the optical layers 2704 and 2708. The sandblasting has the effect of roughening the substrate surface selectively in the regions of the aperture 2709. A roughened surface at aperture 2709 behaves as an optical diffuser which can provide the benefits of a wider viewing angle for the display. In another embodiment, a diffusing surface at aperture 2709 is provided by means of an etching process, where the etch is selectively applied in the regions of apertures 2709 after exposure of photoresist to a photomask. Etch pits or trenches can be created through proper design of the photomask, and the sidewall angles or depths of the pits or trenches can be controlled by means of either a wet or dry etch process. In this fashion optical structures with controlled degrees of diffusive broadening can be created. In this fashion anisotropic diffusers can be created at the substrate surface which deflect light along a preferred optical axis, creating elliptical and/or multi-directional cones of emitted light.

In another embodiment, an etched trench can be provided in substrate 2702 that substantially surrounds the display along the periphery of the array of apertures 2709 (i.e. around the periphery of the active display region). The etched trench performs as a mechanical locating structure for restricting the motion or flowing of an adhesive, such as adhesive 528, used to seal aperture plate 2700 to an opposing substrate.

Further details regarding the materials and processes described above can be found in U.S. patent application Ser. No. 11/361,785, filed Feb. 23, 2006, incorporated herein by reference. For example, that application includes additional materials and processing methodologies regarding the formation of dielectrically enhanced metal mirrors with apertures, light absorbing layers, and spacer posts. Although dielectric mirrors and spacers are described in that application in the context of an integrated (for example MEMS-up) display design, it will be understood that similar processes can be adapted to the fabrication of an aperture plate, such as aperture plate 2700.

In some implementations of the aperture plate 2700, it is desirable to employ a transparent plastic material for the substrate 2702. Applicable plastics include, without limitation, polymethylmethacrylate (PMMA) and polycarbonate. When plastic materials are used, it also becomes possible to utilize an injection molding or stamping process for the formation of spacer posts 2708. In such a process the spacer posts are formed in a mold or a stamper first, before the application of the dielectrically enhanced metal mirror 2704. All of the layers of the dielectrically enhanced metal mirror 2704 would be then be deposited in sequence on top of the substrate which already includes spacer posts 2708. The light absorbing layer 2706 is deposited on top of the dielectric mirror 2704. In order to pattern the aperture window 2709 a special photoresist is applied that uniformly coats the surfaces of the thin films without being disrupted by the presence of spacer posts 2708. Suitable photoresists include spray-on

photoresists and electroplated photoresists. Alternately, a spin-on resist is applied followed by a reflow step that provides an even resist thickness across the thin film surfaces in the areas of apertures 2709. The exposure of the resist, developing, and etching of the thin film layers then proceeds as described above. After the removal of the photoresist, the process is complete. A liftoff process can also be employed to pattern the dielectrically enhanced mirror as described above. The use of a molding or stamping process for the formation of spacer posts 2708 helps to reduce the material costs required in the fabrication of aperture plate 2700.

In some display implementations, aperture plate 2346 is combined with light guide 2348 into one solid body, referred to herein as a unitary or composite backlight, described further in U.S. patent application Ser. Nos. 11/218,690 and 11/528,191, respectively. Both applications are incorporated herein by reference. All of the processes described above for the formation of the dielectrically enhanced metal mirror 2704, for the light absorbing layer 2706, and/or for the spacer posts 2708 can be similarly applied to a substrate which is bonded to or otherwise indistinguishable from the light guide. The surface of the unitary backlight onto which the thin films are applied can be glass, or it could be plastic, including a plastic which has been molded to form spacer posts, such as spacers post 2357.

In one implementation, the spacer posts 2708 are formed or attached to aperture plate 2700 before the aperture plate is aligned to a modulator substrate, such as modulator substrate 2342. In an alternative implementation of display apparatus 2340, the spacer posts 2357 are fabricated on top of and as a part of the modulator substrate 2342, before the modulator substrate is aligned to the aperture plate 2346. Such an implementation was described with respect to FIG. 20 within the aforementioned U.S. patent application Ser. No. 11/361,785.

FIG. 12 is a cross sectional view of a display according to an illustrative embodiment of the invention. The display assembly 2800 comprises a modulator substrate 2802 and an aperture plate 2804. The display assembly 2800 also includes a set of shutter assemblies 2806 and a reflective aperture layer 2808. The reflective aperture layer 2805 includes apertures 2810. A predetermined gap or separation H12 between the substrate 2802 and 2804 is maintained by the opposing set of spacers 2812 and 2814. The spacers 2812 are formed on or as part of the modulator substrate 2802. The spacers 2814 are formed on or as part of the aperture plate 2804. During assembly, the two substrates 2802 and 2804 are aligned so that spacers 2812 on the modulator substrate 2802 make contact with their respective spacers 2814.

The separation or distance H12 of this illustrative example, is 8 microns. To establish this separation, the spacers 2812 are 2 microns tall and the spacers 2814 are 6 microns tall. Alternately, both spacers 2812 and 2814 can be 4 microns tall, or the spacers 2812 can be 6 microns tall while the spacers 2814 are 2 microns tall. In fact, any combination of spacer heights can be employed as long as their total height establishes the desired separation H12.

Providing spacers on both of the substrates 2802 and 2804, which are then aligned or mated during assembly, has advantages with respect to materials and processing costs. The provision of a very tall (e.g. 8 micron) spacer, such as spacer 2708, can be costly as it can require relatively long times for the cure, exposure, and development of a photo-imageable polymer. The use of mating spacers as in display assembly 2800 allows for the use of thinner coatings of the polymer on each of the substrates.

In another implementation, the spacers 2812 which are formed on the modulator substrate 2802 can be formed from

the same materials and patterning steps that were used to form the shutter assemblies 2806. For instance, the anchors employed for shutter assemblies 2806 (similar to anchors 2356) can also perform a function similar to spacer 2812. In this implementation a separate application of a polymer material to form a spacer would not be required and a separate exposure mask for the spacers would not be required.

The display assembly 2900 of FIG. 13A illustrates one methodology for aligning a modulator substrate and an aperture plate, according to an illustrative embodiment of the invention. The display assembly 2900 comprises modulator substrate 2902 and aperture plate 2904. The display assembly 2900 also comprises a set of shutter assemblies 2906 and a reflective aperture layer 2908, including apertures 2910. A predetermined gap or separation between the substrate 2902 and 2904 is maintained by the spacers 2912. The spacers 2912 are formed on or as part of the aperture plate 2904. The display assembly 2900 also includes a set of alignment guides 2914. These alignment guides are formed on or as part of the modulator substrate 2902. When the modulator substrate 2902 and aperture plate 2904 are assembled together, the gap between the alignment guides 2914 and the spacers 2912 is quite close, in some cases less than 1 micron. By capturing the spacer posts between the closely spaced alignment guides, sideways motion between the modulator substrate 2902 and the aperture plate 2904 is restricted, thereby maintaining the alignment between the shutters 2906 and the aperture 2910.

In various implementations, the alignment guides 2914 are ring or doughnut-shaped. In other implementations, the alignment guide 2914 is a simple slot which captures a wall like shape from the aperture plate 2904. The alignment slots can be oriented parallel to either or both edges of the modulator substrate 2903. Having alignment slots with different, and preferably perpendicular, orientations helps to prevent motion in any direction parallel to the plane of the substrate 2902, though other orientations may also be employed. The alignment guides 2914 can be placed either between pixels, within pixels, or external to the array of pixels along the periphery of the display.

Alternate means of maintaining alignment between modulator substrates and aperture plates are possible. In one implementation an adhesive, such as adhesive 528 in FIG. 5, is provided for holding two substrates together in lateral alignment. In this implementation an alignment device, for example, a mechanical platform equipped with translational motor drives and an alignment camera, is utilized to hold the two substrates in their proper orientation while an adhesive, such as adhesive 528, is dried or cured in place. Epoxies that are partially or totally cured by means of UV radiation are particularly useful as adhesives in this implementation. In implementations where the adhesive is applied at the periphery of the display assembly, it is referred to as an edge seal or gasket seal. In some implementations the edge seal adhesive contains glass or polymer beads which act as spacers for maintaining a predetermined gap or spacing between the opposing substrates.

The display assembly 2950 of FIG. 13B illustrates another means for aligning a modulator substrate to an aperture plate, according to an illustrative embodiment of the invention. The display assembly 2950 comprises modulator substrate 2952 and aperture plate 2954. The display assembly 2950 also comprises a set of shutter assemblies 2956 and a reflective aperture layer 2958, including apertures 2960. A predetermined gap or separation between the substrate 2952 and 2954 is maintained by the opposing set of spacers 2962 and 2964.

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The spacers **2962** are formed on or as part of the modulator substrate **2952**. The spacers **2964** are formed on or as part of the aperture plate **2954**.

The spacers **2962** and **2964** are made of different materials. For the embodiment of display assembly **2950** the spacers **2962** are made of a heat reflowable material such as solder while the spacers **2964** are made of a material which is substantially solid or has a melting or softening point considerably higher than that of spacer **2962**. The material in use for substantially solid spacer **2964** can be any of the materials described above with respect to spacer post **2708**, including the materials listed in the incorporated U.S. patent application Ser. No. 11/361,785, or it can be any of the materials described below with respect to conductive spacer **3112**.

The spacer **2962**, also referred to as a solder bump, can be made of a number of different metals or metal alloys commonly used for the soldering of electrical connections. Exemplary alloys include, without exclusion, Pb—Sn alloys, Pb—In alloys, Sn—Sn alloys, In—Cu—Sn alloys, Au—Sn alloys, Bi—Sn alloys, or the substantially pure metals In, Sn, Ga or Bi. Such alloys are designed to liquefy or reflow at temperatures in the range of 150 to 400 Centigrade and to wet the surfaces of two opposing contact materials. After cooling and solidification the solder materials join together (and optionally electrically connect) the two opposing contact materials, acting as an adhesive. For the application illustrated by display assembly **2950** the solder material **2962** acts as an adhesive link between spacer post **2964** and the modulator substrate **2952**. Non-metallic reflow materials are also applicable for use as spacer **2962**. These materials include glass frit materials, such as mixtures of barium-silicate or lead-silicate glasses or thermoplastic polymers, such as polyethylene, polystyrene, or polypropylene, and/or natural and synthetic waxes such as carnauba wax, paraffin, or olefin waxes.

The assembly process for display **2950** would proceed as follows. First the spacer materials **2962** and **2964** would be fabricated onto their respective substrates. Next the two substrates **2952** and **2954** would be assembled together with roughly the correct lateral alignment. Next the two substrates would be heated so as to liquefy or reflow the solder material **2962**. Once molten, the material **2962** would proceed to wet the surface of the substantially solid and opposing spacer post **2964**. Simultaneously, the surface tension of the now liquid material **2962** will act to minimize its surface area. The resulting capillary forces have the effect of pulling or sliding the two substrates **2952** and **2954** laterally into a more perfect alignment. After cooling and solidification the two substrates are locked into alignment by the adhesive properties of the solder material **2962**.

In an alternate implementation the substantially solid material can be fabricated onto the modulator substrate while the heat reflowable material is fabricated onto the aperture plate. In another implementation both the solid and reflow materials are formed sequentially onto one or the other of the modulator substrate or the aperture plate. For that implementation the solder material is designed to wet and join to a bonding pad located on the opposing substrate.

There are other bonding geometries where a heat reflowable material can be used to ensure the alignment between opposing substrates. In one implementation solder bumps are fabricated on both of the substrates, and the bumps or beads of solder material are merged or joined during the reflow process. In this implementation a substantially solid spacer material, such as spacer **2964** is not employed. The gap between the two substrates is determined by the average volume of the solder bumps after solidification, which can be controlled by

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means of the fabricated dimensions for the solder bumps prior to assembly. In another implementation the spacer post **2964** is replaced with a detent or solder receptacle structure, such as a ring or a square frame formed on one of the two substrates with an indent at the center. The molten solder tends to wet and fill the gap at the center of the ring, thereby pulling the opposing substrates into alignment. Similar processes related to the alignment of semi-conductor packages are described in further detail in U.S. Pat. No. 5,477,086, the entirety of which is incorporated herein by reference.

In some implementations the heat reflowable material is disposed within or between each of the pixels in the array. In other implementations the pairing of reflow materials to corresponding posts, receptacles, or bond pads on the opposing substrate can be arranged at the periphery of the display or at the outside corners of the display assembly. When the reflow material is disposed at the periphery of the display it can, in some implementations, serve a further purpose similar to epoxy **528** (see FIG. **5**) as a sealing or gasket material.

FIGS. **14A** and **14B** are top views of a display assembly **3000**, similar to the shutter assembly **2200** of FIGS. **6A** and **6B**, in opened and closed positions, respectively, according to an illustrative embodiment of the invention. The display assembly **3000** includes a shutter assembly, including shutter **3002**, supported over a reflective aperture layer **3004**. The shutter assembly also includes portions of opposing actuators **3008** and **3010**. In display assembly **3000** the shutter is connected to the modulator substrate (not shown), such as modulator substrate **2342** via the actuators **3008** and **3010** and the anchors **3006** and **3007**. The reflective aperture layer **3004** is formed on a separate substrate, such as aperture plate **2346**. The shutter assembly **3001** is suitable for inclusion in an array of light modulators included in a display apparatus.

The shutter **3002** includes three shutter apertures **3012**, through which light can pass. The remainder of the shutter **3002** obstructs the passage of light. The reflective aperture layer **3004** includes apertures **3014** which also allow the passage of light. In FIG. **14A**, where the shutter is in the open position, the apertures **3012** and **3014** are aligned to allow passage of light. In FIG. **14B**, where the shutter is in the closed position, the shutter **3002** obstructs the passage of light through apertures **3014**.

The display apparatus **3000** includes spacer posts **3020** which function in a manner similar to spacer posts **2357** of display apparatus **2340** for maintaining a predetermined gap or spacing between opposing substrates. The spacer posts **3020**, however, provide an additional function of ensuring the proper alignment between the shutter **3002** and the apertures **3014** by fitting between motion stops **3022**, which are solid extensions of the shutter **3002**. When in the open position, the shutter **3002**, via one set of motion stops, comes into hard contact with the spacer post **3020**. When in the closed position the shutter **3002**, via another set of motion stops **3022**, contacts the spacer post **3020** again. The amount of motion allowed for the shutter **3002** between each of the stop positions, in various implementations, ranges from about 5 to about 50 microns.

The alignment control methodology of display assembly **3000** is effective for the case where both apertures **3014** and spacer posts **3020** are attached to one substrate, e.g. the aperture plate, while the shutter **3002** is attached by means of anchors **3007** to another substrate, e.g. the modulator substrate. In such implementations, despite misalignments of as much as 5 or 10 microns during assembly of the two substrates, a proper alignment between the shutters **3002** and the apertures **3014** can be provided. Thus, a shutter/aperture over-



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lap, e.g. overlap W1 in display apparatus 2300, of as narrow as 1 micron can be maintained.

FIG. 15 is a cross sectional view of a display assembly 3100, according to another illustrative embodiment of the invention. The display assembly 3100 includes a modulator substrate 3102 and an aperture plate 3104. The display assembly 3100 also includes a set of shutter assemblies 3106 and a reflective aperture layer 3108. Additionally, the aperture plate 3104 includes a dielectric isolation layer 3114 and an electrically conductive interconnect 3116. The cross sectional view in FIG. 15 is taken along a line where there are no aperture holes in the reflective layer 3108. A predetermined gap or separation between the substrate 3102 and 3104 is maintained by a set of spacers 3112.

The spacers 3112 of display assembly 3100 include an electrically conductive material. For example, they can be formed from metal posts that are formed by either an electroplating process, an etching process, or a lift-off process. The metals copper, nickel, aluminum, gold, or titanium, without exclusion, are useful for this application. Alternately the posts 3112 can be formed from a composite material, for example, a polymer or epoxy material that is impregnated with metal particles to render it conductive. Alternatively the posts 3112 can be formed from polymer materials that are coated with thin metal films such that the surface is made conductive.

The electrically conductive spacers 3112 are disposed to provide an electrical contact between one electrode of the shutter assemblies 3106 and the electrically conductive interconnect 3116. For instance, as shown in FIG. 15, the interconnect 3116 can be patterned as a metal line that is parallel to one of the row or columns in the display. The spacers 3112 and the interconnect 3116 provide, then, a common electrical connection between electrodes in all of the shutter assemblies 3106 for the given row or column. In this fashion, some of the metal layers used to form an addressing or control matrix for a display, such as display apparatus 2340, can be fabricated on top of the aperture plate 3104 instead of on the modulator substrate 3102. The spacers 3112 can be configured to provide a distinct electrical connection between the light modulators 3106 within each of the pixels in the array to an electrical circuit on the opposing substrate. In an extreme case each of the electrodes for each of the shutter assemblies can be connected to a circuit on the opposing substrate by means of electrically conductive spacer posts, such that the complete control circuit, including transistors and capacitors, can be formed on a substrate that is distinct from or separate from that of the light modulators.

The electrically conductive spacer posts 3112 can be formed onto either the modulator substrate 3102 or the aperture plate 3104 prior to assembly. In one implementation the conductive spacers are formed from gold-alloy studs that are individually placed and bonded by machine onto one or the other of substrates 3102 or 3104 as part of the assembly process. In another implementation the spacers are formed from solder bumps which are either electroplated or stenciled onto one or the other or both of substrates 3102 or 3104 as part of the assembly process. Any of the solder materials listed above with respect to solder bump 2962 can be employed for spacer posts 3112.

The process of matching or making electrical connection between a spacer posts and a landing zone on the opposing substrate can include a reflow process, such as an interdiffusion or a soldering process, so that a good electrical contact is made between the two surfaces.

Although the display assembly 3100 is illustrated as part of a MEMS-down configuration, an analogous use for electrically conductive spacer posts can also be found in the MEMS-

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up configuration as with, for example, the display apparatus 2300. For a MEMS-up configuration both the light modulators and the reflective aperture layer are formed on the same substrate, while the electrically conductive interconnects, such as interconnects 3116 are formed on an opposing substrate, such as a cover plate. Conductive spacers, such as spacers 3112, would then make electrical connection between the modulator substrate and the cover plate. The invention is particularly useful for applications where the cover plate also acts as a touch-screen input device. Electrical connections between substrates, especially where connections are provided for each pixel in the array, are useful for providing electrical communication between a touch screen sensor array and a separate substrate that includes a control matrix for the array of pixels.

FIG. 16 is a cross sectional view of another display assembly 3200, according to an illustrative embodiment of the invention. The display assembly 3200 includes a modulator substrate 3202 and an aperture plate 3204. The display assembly 3200 also includes a set of electrical interconnects 3210 formed on the modulator substrate and a set of electrical interconnects 3212 formed on the aperture plate 3204. The two substrates make electrical connections between the interconnects 3210 and 3212 by means of an anisotropic conductive adhesive 3214. The aperture plate also includes a dielectric isolation layer 3211 and a reflective aperture layer 3208. Not shown in this view are shutter assemblies formed on substrate 3202 or any aperture windows in the reflective layer 3208, since this cross sectional view is taken along a line closer to the periphery of the display, outside the array of pixels.

The anisotropic conductive adhesive (i.e. "ACA") 3214 is a polymer adhesive that is impregnated with a collection of solid conducting spheres 3216. When the two substrates 3202 and 3204 are compressed together the conducting spheres become trapped between the contact areas of interconnects 3210 and 3212. An electrical connection is thereby established between the interconnects 3210 and 3212 on opposing substrates. The electrical connection becomes locked in place after the polymer matrix of the ACA is cured or polymerized. The conducting spheres 3216 can range in size from 5 to 50 microns in diameter. The spheres 3216 can be made of a metal, such as nickel, or from alloys such as Ni—Au, Ni—Ag, or Cr—Au. Nickel has sufficient hardness to maintain it's geometry under compressive loading. The conducting spheres can also be fabricated from dielectric materials, such as glass or polymer, which are then coated with a conducting layer such as gold. In an alternate embodiment, metal spheres such as nickel can be coated with another metal with a higher conductivity and resistance to oxidation, such as gold, to reduce contact resistance.

When the conducting spheres are selected for uniform diameter, then the squeezing of the contacts 3210 and 3212 to the conducting spheres 3216 establishes a fixed spacing or gap between the contacts. The conducting spheres 3216 can therefore perform the same function as the spacers 2312 or 2357.

The conducting spheres do not make a continuous contact along an axis parallel to the plane of the substrates. As a result, an electrical connection is generally not established between neighboring pairs of conductors 3210 or pairs of conductors 3212. Therefore a single application of the ACA 3214 can be sufficient to make multiple independent electrical connections between independent sets of interconnects 3210 or 3212. This particular interconnection medium is referred to as an anisotropic conductive medium.



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The ACA **3214** is generally applied by means of a tape or needle dispense over multiple independent electrical contacts. It is particularly useful for making multiple connections along the periphery of a display. For instance it can connect together a series of row interconnects on one substrate to a parallel set of row interconnects on another substrate. This might be useful, perhaps, where the control matrix is built onto the modulator substrate **3202** while driver chips are attached to a parallel set of interconnects on the aperture plate **3204**. The functions of the substrates **3202** and **3206** can also be reversed, so that the modulator substrate is on the bottom, closest to the backlight and the substrate on the other side of the ACA **3214** functions as a cover plate.

The electrically conductive spacers **3112** in display assembly **3100** are preferably used in each and every pixel in the array, although they can be applied on the periphery of the array. The electrically conductive spheres **3216**, which are also spacers, in display assembly **3200** are preferably applied along the periphery of the array of pixels. The spacers **3020** of display assembly **3100**, which perform as motion stops, are preferably used at every pixel in the array. The spacers **2312** or **2357** of display apparatus **2300** and **2340**, respectively, can be placed either within or between each pixel of the array. Similarly the spacers depicted in FIGS. 20 and 21 of U.S. patent application Ser. No. 11/361,785, may also be included with each and every pixel in the array.

The association of a spacer with each and every pixel is not, however, necessary to maintain a desired gap between substrates. A spacer can be associated, for instance, with each group of four pixels or with each group of 16 pixels. In other embodiments the spacers might be restricted to the periphery of the display. Alternatively, as depicted in display assembly **3000**, a display assembly can include multiple spacers per-pixel.

The spacers **2357** in display apparatus **2340**, for instance, are responsible for maintaining an aperture to shutter spacing **H6** that can be as small as 1 micron. Denser spacer placing becomes particularly useful when display resolutions exceed 200 pixels per row or column, or when display diagonals exceed 2 inches. A dense array of spacers is also useful in display apparatus **2300**, for example, for maintaining a uniform pressure on the lubricating fluid **2322**, which might otherwise be disrupted by local pressures, such as finger pressure, applied to the front surface of the display.

The spacers described with respect to this invention can be usefully applied to maintain the gap between substrates in an electrowetting display, such as display apparatus **2500** or **2600**. Any display that employs MEMS-based light modulators, in fact, can benefit from spacers applied within the interior of the array of light modulators. Examples of alternate MEMS-based light modulators include digital mirror devices (DMDs), interference modulation displays (IMODs), and light tap displays or frustrated internal reflection displays. Alignment Apparatus and Techniques

As indicated in the discussions of display apparatus **2300** and **2340** and for the shutter assembly **2200**, the alignment of a shutter assembly to its corresponding aperture is an important design feature for the MEMS light modulator. The overlap, indicated as overlap **2216** or as overlaps **W1** and **W2**, reduces or eliminates light leakage while the MEMS light modulator is in its closed state, a state which is also referred to as a light obstructing state or a dark state. For the MEMS-down display apparatus **2340** the overlap **W2** is established during the cell assembly process, when the two substrates, **2342** and **2346** are aligned and mechanically attached to each other. For display apparatus **2340** the apertures **2347** are formed on the aperture plate **2346** while the shutter assem-

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blies **2341** are formed on or supported from the modulator substrate **2342**. The proper spatial relationship between apertures **2347** and shutter assemblies **2341** can be achieved with precision if a means for accurate alignment of the two substrates **2342** and **2346** can be provided. One method for alignment of the two substrates is made possible by an alignment apparatus **3300**, as illustrated in FIG. 17, according to an illustrative embodiment of the invention.

The alignment apparatus **3300** comprises a stationary chuck **3302**, a set of translational drives or motors **3304**, a vision system **3305**, and a set of UV exposure lamps **3306**. A modulator substrate **3308** is rigidly attached to the chuck **3302**. An aperture plate **3310** is held in place and guided by the motors **3304**. The motors **3304** provide the ability to translate the substrate **3310** in three translational directions, for instance along x and y coordinates within the plane of substrate **3310** and additionally along the z coordinate establishing and varying the distance between the two substrates **3308** and **3310**. Additionally, not shown in FIG. 17, an additional and optional set of three rotational motors can be provided, which ensure both the co-planarity of the substrates **3308** and **3310** and also their proper rotational relationship in the x-y plane. Although all translational motors **3304** are shown attached to the aperture plate **3310**, in other embodiments the motors can be arranged differently between the two substrates. For instance the x-y translation motors can be attached to the aperture plate **3310** while the z-axis translation motor and theta rotation motor (about the z-axis) can be attached to the chuck **3302**.

A variety of motor types are available for the motors **3304**. In some embodiments these motors can be digitally controlled stepper motors, in some cases they can be linear screw drives, and in other cases they can be magnetically-driven solenoid drives. The motors need not be arranged to directly move a substrate, such as substrate **3310**. They can instead be designed to move a stage or platter onto which the working piece or substrate **3310** is rigidly attached. The use of a moving stage is advantageous, since an additional optical measuring system (in some cases a laser interference system) can be provided for the stage which is capable of continuously measuring its translational position to a precision of better than 1  $\mu\text{m}$ . Feedback electronics can then be employed between the motors **3304** and the optical measurement system to improve both the accuracy and stability of the stage position.

In some embodiments of apparatus **3300** both the chuck **3302** and the optional moving stage can be equipped with heaters and/or temperature control devices, to ensure uniform temperature across the substrates **3308** and **3310**. Uniform temperatures help to ensure proper alignment between patterns on the two substrates, particularly for substrates whose diagonals exceed about 20 centimeters.

The alignment apparatus **3300** incorporates a vision system **3305** for detecting the relative positions of the two substrates **3308** and **3310**. In a preferred embodiment, alignment marks are patterned into thin films on each of the substrates **3308** and **3310** (see, for example, the alignment marks **3408** and **3412** in FIG. 18). The vision system is capable of simultaneously imaging alignment marks on each of the two substrates, despite the fact that the marks are located on different surfaces, i.e. at different positions on the z axis.

For the illustrated embodiment, the vision system **3305** incorporates two imaging lenses **3312** and **3313** and either a microscope capable of split-field imaging or two cameras **3314** and **3315**. The vision system **3305** is therefore capable of imaging, substantially simultaneously, two separated sets

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of alignment marks. The two sets of alignment marks are preferably located at the far sides or corners of the modulation array or panel.

In operation, an operator uses the vision system **3305** to view the relative positions of alignment marks, such as marks **3408** and **3412**, and thereby judge the direction and degree of misalignment between the two substrates. The operator can then adjust the alignment between substrates **3308** and **3310**, using drive motors **3304**, until the alignment marks on the two substrates indicate misalignment below an acceptable degree of error. After sufficiently reducing the misalignment, the operator drives the z-axis motor until the spacers, such as any of the spacers **2357**, **2708**, or **2812** and **2814**, on one of the substrates, **3308** or **3310**, contact the opposing substrate, **3308** or **3310**, or opposing spacers. In many instances, due to mis-orientation or non-planarity of the substrates, the operator will need to continually refine the x-y alignment between the substrates as the z-axis distance between the two substrates is decreased. In some embodiments, a final x,y, and theta correction can be made even after contact is established between the substrates. After contact is made, an adhesive **3318** will also make contact between the two substrates. In some embodiments, as the last step in the method **3301**, the adhesive is at least partially cured while the alignment apparatus **3300** holds the two substrates in position. The UV exposure lamps **3306** can be used to initiate or accelerate the curing of the adhesive, thereby bonding the two substrates together. In some embodiments the substrate stage or the chuck **3302** is equipped with heaters to affect a thermal curing of adhesive **3318**. The alignment marks, e.g. marks **3408** and **3412**, are usually patterned and etched at the same time and are printed from the same photomask as the masks used to pattern the apertures, such as apertures **2347**, and the shutter assemblies, such as shutter assembly **2341**, respectively. The alignment marks are therefore designed for a fiducial function, i.e. the operator who achieves sufficient alignment between the alignment marks has confidence that the shutters and apertures in the neighboring array will also be in properly aligned.

According to the discussion of display apparatus **2340**, the overlap **W2** is preferably greater than or equal to 2  $\mu\text{m}$ . In practice an overlap **W2**, which is reliably achieved during manufacture, is determined by a safety margin, designed into the masks, and by an alignment precision or tolerance. The precision or achievable tolerance is based on the design of alignment apparatus **3300**, the design of the alignment marks, and process variables such as temperature, pressure, and the viscosity or plasticity of seal materials. Two examples are provided below for acceptable tolerance design: In the first example, which is tolerant of relatively wide variations in alignment during manufacture, an array of shutters and apertures is designed with a nominal overlap of 22  $\mu\text{m}$ , i.e. if perfectly aligned, the shutters are designed to overlap the apertures by 22  $\mu\text{m}$ . If the apparatus **3300** then enables an alignment repeatability of  $\pm 20 \mu\text{m}$ , the designer can be assured that all (or 99.99% depending on how reliability is specified) of the shutters will have an overlap of at least 2  $\mu\text{m}$ . However, for a dense array of pixels, i.e. for a high resolution display, there is not usually room available in an array design for 22  $\mu\text{m}$  of overlap. Therefore a more precise alignment capability is desired.

In the second example, a nominal overlap of only 1  $\mu\text{m}$  is provided for in the masks, and the apparatus **3300** is designed to provide an alignment precision within  $\pm 1 \mu\text{m}$  between patterns on the first and second substrates. To achieve this precision a) the vision system **3305** a resolution smaller than 1  $\mu\text{m}$ , b) the motors **3304** (or associated translation stages)

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stably drive to and resolve position differences with a resolution smaller than 1  $\mu\text{m}$ , and c) the alignment marks are patterned and etched with edges, dimensions, and/or placements that are precise to a resolution of better than 1  $\mu\text{m}$ . Automated alignment systems with sub-micron precision are available today for purposes of semiconductor mask alignment, optoelectronic component assembly, and micro-medical devices. Representative suppliers of these systems include the Automation Tooling Systems Corp. of Cambridge, Ontario, Canada and the Physik Instrumente LP of Karlsruhe, Germany.

Generally, if attention is paid to the design of the vision system, the drive motors, and the design of the alignment marks, then it possible to provide an alignment apparatus **3300** and an alignment method which is capable of ensuring an overlap **W2** between shutters **2341** and apertures **2347** that is greater than 0  $\mu\text{m}$  and less than 20  $\mu\text{m}$ . In a preferred design, the alignment method is capable of ensuring an overlap **W2** that is greater than 0 microns and less than 2 microns.

The alignment method described above was provided as one example of an alignment method that assigns active control of the motors **3304** to a human operator. In other methods the intervention of an operator is not required to achieve alignment. Intelligent vision (machine vision) systems are available, for example, from the vendors identified above, for the apparatus **3300** (i.e. systems which include digital cameras and computer image processing) that can measure the direction as well-as the amount of misalignment between fiducials on two substrates and then can automatically drive the motors **3304** until the measured misalignment becomes less than a pre-specified level.

The alignment marks or fiducials employed by apparatus **3300** can take many forms, other than those shown or discussed with respect to FIG. **18** below. In some embodiments the operator or the machine vision system is capable of recognizing specific functional patterns on the substrates, such as the shapes of shutter assemblies (e.g. shutters **2202**) or apertures (e.g. apertures **2214**). The vision system thereby measures and minimizes directly the misalignment between shutters and apertures. In another embodiment, the display edges are cut or diced to a precise position with respect to the positions of the shutters and apertures. The vision system thereby measures and minimizes the misalignment between the edges of the two substrates.

After either a human operator or the automatic alignment system brings the substrates into alignment and establishes contact between the two substrates, the UV exposure lamps **3306** can be employed to at least partially cure the adhesive **3318**. The adhesive bonding material **3318** prevents the subsequent relative movement between substrates **3308** and **3310** after alignment has been achieved in apparatus **3300**. Alternate means are available for maintaining alignment between the two substrates after alignment. These alternate means include the use of alignment guides, such as alignment guides **2914**, and heat reflowable spacer materials such as spacer **2962**.

Although the functioning of alignment apparatus **3300** was with the example of display **2340** in the MEMS-down configuration, similar alignment techniques can be useful when applied to the MEMS-up configuration, as illustrated by display apparatus **500**. In display assembly **500** the shutter assemblies **502** are formed on substrate **504** while the black matrix and associated apertures **524** are formed on substrate **522**. The two substrates **504** and **522** can be aligned using alignment apparatus **3300** such that an overlap exists between at least one edge of the shutters **503** and the edge of a corresponding aperture in black matrix **524**. The alignment appa-

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ratus **3300** ensures an overlap between edges of between 0 and 20 microns. In a preferred design, the alignment method ensures an overlap that is greater than 0 microns and less than 5 microns, or in some cases, less than 2 microns.

Although the functioning of alignment apparatus **3300** was described for a display incorporating transverse-shutter-based light modulators, such as shutter assembly **2341**, it will be understood that the alignment apparatus **3300** and alignment method described above can be usefully applied to alternate MEMS light modulator technologies. For instance, the electrowetting modulator array **2600** benefits when the aperture plate **2632** is aligned to the modulator substrate **2630** such that an overlap is established between the edge of the oil **2610** and the edge of apertures **2617** in the light-obstructing, filtered, or dark state. Similarly rolling actuator light modulators, such as light modulator **220** can be fabricated and aligned in similar fashion, wherein an overlap is provided between the light obstructing edge of the roller-actuator-modulator on a first substrate and the edge of a corresponding aperture which has been patterned on a second substrate.

Other non-shutter-based modulators can benefit from the alignment apparatus **3300** and method described above. For instance, a MEMS interference modulator or a MEMS light tap modulator, such as light modulator **250**, fabricated on a first substrate can be aligned to the edge of a black matrix fabricated on a second substrate. Details of these light modulators can be found in U.S. Pat. Nos. 6,674,562 and 5,771,321, incorporated herein by reference.

#### Panel Fabrication Processes

Manufacturing productivity is increased whenever the modulator arrays for multiple displays can be built in parallel fashion on the same glass or plastic substrate. Large glass substrates, referred to as panels, and associated fabrication equipment, are now available in sizes up to 2 meters square. FIG. **18** illustrates how multiple arrays of MEMS light modulators can be formed onto one large modulator substrate **3402** while multiple arrays of aperture holes can be formed on a large aperture plate **3404**, according to an illustrative embodiment of the invention. The panel **3402** includes a set of 6 modulator arrays **3406** plus a set of four modulator alignment marks **3408**. The panel **3404** includes a set of six aperture arrays **3410** plus a set of four aperture alignment marks **3412**. Each of the modulator arrays **3406** is designed to correspond to one of the aperture arrays **3410**, such that when the panels **3402** and **3404** are aligned and sealed together, the corresponding modulator array—aperture array pairs will each form a display assembly, also referred to as a cell assembly. A single alignment and sealing operation between substrates **3402** and **3404**, then, suffices to simultaneously align and seal 6 cell assemblies. For the example shown in **18**, the glass panels **3402** and **3704** are 30 cm in diagonal while each of the cell assemblies or display areas would be 10 cm in diagonal. In other embodiments, panels as large as or larger than 50 cm in diagonal may be employed to fabricate up twenty five 10 cm diagonal displays per panel.

Also shown are the epoxy adhesive lines (one type of seal material) **3414**, and spacer posts **3416** added to each of the arrays on the aperture plate **3404**. A variety of spacers are applied to the interior of each array on aperture plate **3404**, as described with respect to display assemblies **2340**, **2700**, **2800**, **2900**, and **3000** and **3100**, and **3200** above. The process for applying the adhesive will be described below with respect to the cell assembly step **3614**.

A panel assembly **3500**, after completion of alignment and seal of panels **3402** and **3404**, is illustrated in the FIG. **19**, according to an illustrative embodiment of the invention. Successful alignment of the two substrates is indicated by the

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nesting of the modulator alignment marks **3408** within the aperture alignment marks **3412**. The alignment marks can be designed such that a nominal 1  $\mu\text{m}$  gap is allowed between the inner edge of the mark **3412** with the outer edge of the mark **3408** (the magnitude of these gaps is exaggerated in FIG. **19** for purposes of illustration). In this alignment design, the operator and/or automatic alignment system adjusts the relative position of the substrates in the tool **3300** until appropriate gaps are visible in both the x and y directions for the nested alignment marks, e.g., until none of the lines are crossed or touching. When the appropriate gaps are visible the alignment is considered successful, i.e. misalignment has been reduced to within an acceptable error and the expected overlap between modulators and apertures in each of the arrays **3406** and **3410** has been achieved. The nominal gap between alignment marks can be designed to match the anticipated precision of the alignment process, e.g. the gap can be 10 microns, or 2 microns, or 1 micron depending on the alignment precision desired. In an alternate design, one alignment mark is a circular dot while the other mark is shaped as a ring. A gap can be designed between the dot and the ring corresponding to the desired alignment precision. In some alignment machine designs, a gap between alignment marks is not required; instead the machine uses a digital camera to estimate the center points of both dot and ring. The alignment software then seeks to align the center-points of dot and ring.

The two panels **3402** and **3404** are bonded in place by an adhesive. The curing of this adhesive is described below with respect to the cell assembly step **3620**.

FIG. **19** also illustrates a set of dicing lines **3502** superimposed upon the panel assembly **3500**. The dicing lines **3502** mark the lines along which the panel will be cut so that individual arrays, also referred to as displays or cell assemblies, can be separated from panel. The separation process, also referred to a singulation, can be accomplished by means of a scribe and break method. In this process a diamond or carbide tip is used to scratch a line along the surface of the glass panels at lines **3502**. A simple bending process can then be used to break the panels along the scribe lines. In another embodiment the separation or singulation process is accomplished by means of a dicing saw. It is not necessary that both substrates **3402** and **3408** be cut along the same dicing lines. It is often advantageous that the modulator substrate be diced to a perimeter width that is wider than that prescribed for the aperture substrate. This allows room for the bonding of driver chips, after cell assembly is complete, on the edge of the modulator substrate.

#### Cell Assembly Methods Including Fluid Fill

FIG. **20** illustrates a first method **3600** for assembling a display apparatus (also referred to as cell assembly method **3600**) incorporating MEMS light modulators, according to an illustrative embodiment of the invention. The method **3600** begins with the provision of two substrates (steps **3602** and **3604**) upon which the display components are fabricated (steps **3606**, **3608**, and **3610**). The method continues with the application of spacers (step **3612**) and sealing materials (step **3614**) to one or the other of the two substrates; the substrates are then aligned and bonded together. The method includes the separation or singulation of individual displays from a larger panel assembly (step **3622**) and the filling of the gap between the two substrates with a fluid or lubricant (step **3624**). Finally, a filling hole is sealed (step **3626**).

A first embodiment of method **3600** will be described with respect to a MEMS-down display assembly, as illustrated by display apparatus **2340** or **2600**. A second embodiment, for assembly of displays in the MEMS-up configuration, will be described thereafter.

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The cell assembly method **3600** for MEMS-down displays begins with provision of two substrates at steps **3602** and **3604**. Both of these substrates are transparent, made from glass or plastic. The assembly method continues with the fabrication of a control matrix, at step **3606**, and the fabrication of the MEMS modulator array, at step **3608**. In a preferred embodiment both the control matrix and the modulator array are fabricated onto the first substrate, referred to as the modulator substrate. Examples include substrates **2342** and **2630** of FIGS. 7 and 10, respectively. As discussed with respect to display assembly **3100**, however, there are embodiments where the control matrix can be fabricated on a substrate distinct from the modulator substrate and be electrically connected to it by means of electrically conductive spacers. Further detail on the fabrication of the modulator substrate can be found in the U.S. patent application Ser. No. 11/361,785 referenced above.

The MEMS-down assembly method **3600** proceeds at step **3610** with the fabrication of an aperture layer. The aperture layer is fabricated onto the second substrate, which is preferably made of a transparent material, e.g. plastic or glass. In the MEMS-down configuration the second substrate is referred to as the aperture plate. Illustrative operative plates include aperture plates **2346** or **2632** of FIGS. 7 and 10. In other MEMS-down embodiments the second substrate, on which the aperture layer is fabricated, is also be utilized as a light guide. In some embodiments, the aperture layer is composed of a light absorbing material which is patterned into a series of apertures. In a preferred embodiment, described with respect to aperture plate **2700**, the aperture layer is designed to reflect light incident from the substrate back toward the substrate. Illustrative reflective aperture layers include reflective aperture layers **2616** or **2704** of FIGS. 10 and 11, respectively.

The method **3600** continues at step **3612** with the application of spacers. Any of the spacers illustrated by the spacers **2357**, **2708**, **2812**, **2814**, **2912**, **2914**, **2962**, **2964**, **3020**, or **3112** including the fabrication methods described therefore can be incorporated at step **3612**. The spacers may be formed onto either or both of the first and second substrates.

The method **3600** continues at step **3614** with the application of a seal material, such as the epoxy seal material **528**. The seal material can be applied to either or both of the first and second substrates employed by the method **3600**. The seal material is an adhesive bonding material, which will maintain the position of the first and second substrates after the alignment step. The seal material is also used to contain the fluid, to be added at step **3624**, within the gap between the two substrates. Applicable seal materials can be a polymer material such as an epoxy, an acrylate, or a silicone material or the seal material can be formed from a heat-reflowable solder metal such as solder bump **2962**. In some embodiments the seal material can be a composite material, such as the anisotropic conductive adhesive **3214**. The seal material can be dispensed from a nozzle, which moves along the periphery of each of the modulator or aperture arrays, as shown for display panel **3404** in FIG. 18. The seal material **3414** does not completely encircle the periphery of each display area on display panel **3404**. A gap **3418**, referred to as the filling hole, is intentionally left in the peripheral seal to accommodate the filling of the cell with fluid at step **3624**.

After dispense, a seal material undergoes a cure step to become relatively hard and rigid. Although seal material may be partially cured as part of the step **3614**, in many embodiments a final cure does not occur until one of the later steps **3618** or **3620**. The seal material may be formulated to allow for many alternate types of curing, including desiccation curing, UV or ultraviolet curing, thermal curing, or microwave

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curing. When employing an alignment tool, such as the apparatus **3300**, a UV-cured epoxy can be preferred.

As indicated in FIGS. 18 and 19, the steps for fabrication of the control matrix **3606**, fabrication of MEMS modulators **3608**, fabrication of the aperture layer **3610**, application of spacers **3612**, and application of seal material **3614** can all be performed at the panel level where multiple displays are fabricated simultaneously on a large glass or plastic panel. Alternately, these steps may be performed for individual displays on smaller substrates. Further fabrication details for assembly steps **3606**, **3608**, **3610**, and **3612** can be found in the U.S. patent application Ser. No. 11/361,785, referenced above.

The method **3600** continues at step **3616** with the optional dispense of a conductive adhesive. If the spacers or the seal material added at steps **3612** and **3614** do not have a conducting property, then it is often advantageous to add an additional adhesive with this property. The conductive adhesive added at step **3616** allows for an electrical connection between the control matrix on the first substrate and the aperture layer on the second substrate. The adhesive added at step **3616** is usually located at some point along the periphery of the display area.

The method **3600** continues at step **3618** with the alignment of the first and second substrates, as was described with respect to the alignment apparatus **3300** in FIG. 17. The alignment apparatus **3300** includes a camera and/or microscope system for confirming that the alignment is accurate to within an acceptable degree of error. The first and second substrates are brought into contact by means of the spacers as part of the alignment step **3618**.

As part of the alignment step **3618** the adhesive bonding material is at least partially cured to bond or maintain the relative positions of the two substrates. The alignment apparatus **3300** includes heaters and/or UV exposure lamps to affect cure of the adhesive. In some embodiments the whole perimeter seal, such as seal **3414**, is at least partially cured as part of step **3618**. In other embodiments a plurality of uv-curable adhesive dots is provided on the substrates prior to alignment, in addition to a thermally-curable seal material **3414**. For this embodiment only the epoxy dots are cured as part of the alignment step **3618**, while the remainder of the seal material is cured later, at step **3620**.

The method **3600** continues at step **3620** with the cure of the seal material. In many embodiments the proper alignment between first and second substrates can only be maintained when the seal material behaves as a relatively rigid adhesive. The adhesive cure at step **3620** ensures the rigidity of the seal. The cure at step **3620** can be carried out as either a thermal, a UV, or a microwave cure. In some embodiments the seal is cured at step **3620** by placing the assembly into an oven, or UV or microwave exposure system, under pressure or between the plates of a press. The press helps to minimize bending or warping in the substrates while the adhesive is being cured. The press helps to ensure that the gap, such as gap **H5** or **H9** (shown with respect to display assemblies **2340** and **2390**), are maintained by ensuring a rigid contact of each substrate to the spacers, such as spacers **2357**.

The method **3600** continues at step **3622** with the optional separation of individual display arrays from a large panel containing multiple arrays. Such separation is only required if the cell assembly steps, up until this point, have proceeded according a large panel process, as described in FIGS. 18 and 19. If the modulation substrate and aperture plates are fabricated as individual displays at steps **3606** to **3614**, then no

singulation or separation step is necessary. The separation may be accomplished by either a scribe and break process or by a dicing saw.

The method **3600** continues at step **3624** with the filling of the display assembly with fluid. As indicated in the discussions of display apparatus **500** and **2340**, the two substrates of a display apparatus are preferably separated by a gap, such as the gap **H5**, and the gap is filled by a fluid, such as working fluid **530** or **2352**. For many displays the fluid acts as a lubricant which substantially surrounds the MEMS light modulators. The fluid also has defined electrical and optical properties as discussed above.

For many applications it is desirable to fill the display assembly with liquid while avoiding the entrapment of gas bubbles in the gap formed between the two substrates. Gas bubbles which form on surfaces of the MEMS light modulators will interfere with the actuation of those modulators. A bubble-free filling process can be accomplished by utilizing a vacuum atmosphere at some point during the fluid fill process.

The details of the fluid filling process (step **3624**) will be described with respect to the fluid filling apparatus **3700** which is illustrated in FIG. **21**, according to an illustrative embodiment of the invention. The fluid fill apparatus is formed from a vacuum chamber **3702** which is partially filled with a reservoir of the working fluid **3704**. An aligned and partially sealed cell assembly or panel assembly, such as panel assembly **3500**, is suspended above the fluid reservoir by a wand **3706**, or alternately by a moveable platter. Attached to the vacuum chamber is a port **3708** leading to a vacuum pump and a port **3710** used to vent the interior of the vacuum chamber to atmospheric pressure. Valves are associated with each of the ports **3708** and **3710**, although not shown in FIG. **21**.

In operation, the process for filling the gap between the substrates in a panel assembly, such as assembly **3500**, is a two-step process. First the air or other gas is removed from between the two plates and, second, the gap is filled by the fluid. Air is removed from between the plates when the valve to the vacuum pump is opened and the whole chamber **3702** is reduced to a pressure substantially below 1 torr. Next the vacuum valve is closed and the wand **3706** is used to immerse the panel assembly **3500** into the reservoir **3704** of the working fluid. Once immersed, the vent valve is opened to the air, or to clean nitrogen or argon gas from a bottle. The returning air brings the pressure on all fluids back to atmospheric pressure (or pressures greater than 600 torr). Under pressure, the working fluid is then forced into the gap between the substrates of cell assembly **3500**. When the cell assembly is removed from the chamber **3702** the cell assembly is filled by the fluid, thus completing the assembly step **3624**.

In an alternate design, the panel assembly **3500** need not be suspended by a moveable wand, such as wand **3706**. Instead the panel assembly can be fixed in place and the lubricant **3705** can be moved into or out of the vacuum chamber **3702** by means of a series of valves. The chamber is evacuated while fluid is largely absent from the chamber. After evacuation, the fluid level in the chamber is increased by flowing additional fluid into the chamber. Fluid is added until the assembly **3500** is immersed in fluid. After immersing the panel in fluid the system is vented to atmospheric pressure to fill the gap with fluid.

In another embodiment the chamber **3702** is not filled with a liquid, as in liquid **3704**, but is instead backfilled with a gas after evacuating the chamber. Examples of backfill gases include inert gases (argon, nitrogen), vapor phase lubricants, certain reactive gases, or any combination of the above. The

reactive gases are those that can react with or be deposited onto the moving surface of the MEMS modulators. They can chemically pacify or reduce the stickiness of moving surfaces by reducing its surface energy. Examples include, without limitation, dimethyldichlorosilane (DDMS), tridecafluoro-1, 1,2,2-tetrahydrooctyltrichlorosilane (FOTS), and heptadecafluoro-1,1,2,2-tetrahydrodecyltrichlorosilane (FOTS). Vapor phase lubricants are gases that remain in the vapor phase substantially throughout the operation of the device, and are similarly capable of pacifying surfaces. Examples include, without limitation, sulphur hexafluoride, and the vapor phase forms of methanol, ethanol, acetone, ethylene glycol, silicone oils, fluorinated silicone oils, dimethylsiloxane, polydimethylsiloxane, hexamethyldisiloxane, and diethylbenzene, or any mixture of the above.

The fluid filling process within chamber **3702** can be executed on either the cell level or the panel level. In assembly process **3600** the singulation step **3622** precedes the fluid filling step **3624**, meaning that the cell assemblies for individual displays are loaded into vacuum chamber **3702** for fluid filling. The vacuum fill chamber **3702** can include a platter capable of holding and immersing multiple individual displays in a single pump-down operation—so that multiple displays can be filled with fluid at the same time. Alternately it is possible to reverse the orders of these steps and load a complete panel assembly, such as assembly **3500**, into the vacuum chamber. The gaps within each of the displays on the panel are then evacuated and filled at the same time. The dicing or singulation process **3622** then occurs after the fluid filling step **3624** is complete.

A cell assembly is completed in the method **3600** with the sealing of the filling hole, at step **3626**. The fluid was allowed or forced into the space between substrates at step **3624** through the filling hole **3418** that was left in the perimeter seal at step **3614**. This hole is filled with an adhesive at the end of the assembly process to prevent leakage of the fluid out of the display assembly. As part of step **3626** and prior to sealing the fill hole, pressure can be applied to the cell via a press. The press compresses the two substrates, forcing the spacers fabricated on one substrate, into intimate contact with the other substrate. This establishes a uniform gap or spacing between the two substrates. The fill hole **3418** is then sealed with adhesive prior to removal of pressure from the display. Once sealed, the closed and fluid-filled chamber within the cell prevents the substrates from separating under ambient conditions. The adhesive employed at step **3626** may be a polymer adhesive that is cured using either thermal curing, UV curing, or microwave curing. The final steps for assembling a display, after completion of the method **3600**, are often referred to collectively as the module assembly process. The module assembly incorporates the steps of attaching a silicon chip or chips comprising control and drive circuitry directly to the glass substrate, bonding flexible circuits for interconnecting the display to external devices, bonding optical films such as contrast filters, affixing a backlight, and mounting the display into a support structure or enclosure. The flexible circuit may be comprised of simple interconnects or may contain additional electrical elements such as resistors, capacitors, inductors, transistors or integrated circuits.

The cell assembly method **3600** will now be reviewed for its application to the MEMS-up display configuration, examples for which are given by display assemblies **500** and **2400** of FIGS. **5** and **8**. For the MEMS-up display configuration both the control matrix and the MEMS modulator array are fabricated on the first substrate at steps **3606** and **3608**.

Examples are given as modulator substrates **504** or **2418**. An aperture layer is deposited on the second substrate at step **3610**.

As discussed with respect to display assembly **3100** there are embodiments where the MEMS modulator array is fabricated on the first substrate while the control matrix can be fabricated on the second substrate. The two substrates are in electrical communication by means of conductive spacers.

For the MEMS-up display configuration the second substrate is referred to as a cover plate, such as cover plate **522**. The aperture layer, fabricated at step **3610**, is referred to as a black matrix layer, such as black matrix **524**, and is patterned into an array of apertures. The black matrix layer is preferably comprised of a light absorbing material to improve the ambient contrast of the display. After assembly, the black matrix apertures preferably overlap the MEMS light modulators which are located on the modulator substrate.

For the MEMS-up display assembly method **3600** the cover plate, i.e. the second substrate provided at step **3604**, is preferably made of a transparent material, i.e. plastic or glass. For the MEMS-up assembly method, however, the modulator substrate provided at step **3602** can be made from an opaque material, such as silicon. For instance, for a reflective MEMS-up display, the first substrate, e.g. silicon, can be coated with a reflective layer at one of steps **3606** or **3608**. For a transmissive MEMS-up display, an opaque material employed for the first substrate can be etched with an array of through-holes at the positions of apertures, such as apertures **508**.

For the MEMS-up display assembly **3600**, spacers are applied at step **3612**, and seal material is applied at step **3614** to either of the first or second substrates, i.e. either the modulator substrate or the cover plate.

The subsequent steps in a MEMS-up display assembly method **3600** are similar to the MEMS-down display assembly method **3600**, including the alignment step **3618**, the cure of seal material, step **3620**, the separation of individual displays from the panel, step **3622**, and fluid filling at step **3624**.

As described with respect to the alignment apparatus **3600**, the assembly method **3600** in either the MEMS-up or the MEMS-down configuration is applicable to a number of alternate MEMS light modulator technologies, including electrowetting displays and rolling-actuator displays. The MEMS-up display assembly method **3600** is particularly applicable to interference modulator displays and MEMS light tap modulator displays.

FIG. 22 illustrates an alternative method for assembling a display apparatus incorporating MEMS light modulators. The method **3800** can be employed for assembling displays into either the MEMS-down configuration or the MEMS-up configurations as described with respect to the method **3600**. Similar to method **3600**, the assembly method **3800** begins with the provision of two substrates (steps **3802** and **3804**) upon which the display components are fabricated (steps **3806**, **3808**, and **3810**). The method **3800** continues with the application of spacers (step **3812**) and sealing materials (step **3814**) to one or the other of the two substrates. The method **3800** also includes filling the gap in a display assembly with fluid (step **3818**). However, in contrast to the method **3600**, the order of fluid filling (step **3818**) and display assembly (steps **3820**, **3822**, and **3824**) are reversed. The assembly method **3800** is sometimes referred to as the one-drop fill method.

The assembly method **3800** begins with the provision of first and second substrates, steps **3802** and **3804** and continues with the fabrication of the control matrix (step **3806**), the fabrication of a MEMS modulator array (step **3808**), the fabrication of an aperture layer (step **3810**), and the applica-

tion of spacers (step **3812**). These steps comprise substantially the same assembly processes as were used for corresponding steps in the assembly method **3600**.

The method **3800** continues at step **3814** with the application of a seal material. Similar seal materials and similar dispense methods can be applied at step **3814** as were used for the seal application step **3612**. For the step **3814**, however, no gap or filling hole is left in the seal material around the periphery of the active areas of the display.

An optional conductive adhesive application, step **3816**, follows which is similar to the adhesive application step **3616**.

The method **3800** continues at step **3818** with the application of a liquid. The applicable liquids, comprising lubricating and other electrical, mechanical, and optical properties were described above with respect to display apparatus **500**. For a liquid filling step (step **3800**), a vacuum filling apparatus, such as apparatus **3700** is not necessary. A correct volume of fluid can be dispensed directly onto the open face of one of the first or second substrates. The fluid is preferably dispensed on the second substrate on which the aperture layer is formed, as this substrate generally has no MEMS components with cavities or re-entrant surfaces where air bubbles might collect. When the substrates are large panels incorporating multiple displays, as in panel **3404**, a correct volume of fluid is dispensed into the active area of each array. Generally, the fluid will spread over the face of the substrate until confined by the perimeter of seal material **3414**. A correct volume of fluid will completely fill the cavity defined by the perimeter seal. In some embodiments an optical measurement tool is used to determine an accurate volume for each cavity before filling—by measuring actual perimeter dimensions for individual arrays on the panel.

The method **3800** continues at step **3820** with the alignment of the two substrates. As the lubricating fluid has already been applied to one of the substrates, the alignment apparatus required for step **3800** will differ from that shown by apparatus **3300**. As a primary difference, the alignment operation is preferably carried out under reduced pressure or vacuum conditions. This means that the first and second substrates, as well as many of the moving parts and parts of the vision system provided for alignment are now operated within a vacuum chamber, referred to as an alignment chamber.

In operation the two substrates would be introduced to the alignment chamber and the chamber would be evacuated. To prevent evaporation of the fluid (already dispensed as at step **3818**), the chamber may be backfilled to an equilibrium vapor pressure of the lubricating fluid. After the two substrates are aligned and brought together, the lubricating fluid will make contact with the surface of each of the two substrates and will substantially surround each of the moving parts of the MEMS light modulators. After the substrates are in contact and the fluid has wet all surfaces, the alignment chamber is vented back to atmospheric pressure (at step **3822**). A partial cure can also be applied to the adhesive after the substrates have been brought into contact. The adhesive can be cured by either thermal means or by means of UV lamps installed within the vacuum chamber.

In some embodiments, where the lubricating fluid has a high vapor pressure, i.e. where it can evaporate quickly at ambient temperatures, it may not be practical to dispense the fluid at step **3818** before the panels are introduced into the alignment chamber. For this embodiment, after the alignment chamber has been evacuated and backfilled with a vapor pressure of the lubricant, a nozzle can be provided which dispenses the lubricating fluid onto one of the substrates immediately before the step of aligning of the two substrates.

To the extent that the seal material was not completely cured during the alignment operation at step 3820, a further curing step is applied at step 3824. The cure at step 3824 can be carried out as either a thermal, a UV, or a microwave cure.

The method 3800 is completed at step 3826 with the optional separation of individual display arrays from a large panel containing multiple arrays. Such separation is only required if the cell assembly steps up to this point have proceeded according a large panel process, as described in FIGS. 18 and 19. If the modulation substrate and aperture plates where fabricated in the form of individual displays at steps 3806 to 3814, then no final separation step is necessary. The separation may be accomplished by means of either a scribe and break process or by use of a dicing saw.

The final steps for assembling a display, after completion of the method 3600, are often referred to collectively as the module assembly process. The module assembly incorporates the steps of attaching a silicon chip or chips comprising control and drive circuitry directly to the glass substrate, bonding flexible circuits for interconnecting the display to external devices, bonding optical films such as contrast filters, affixing a backlight, and mounting the display into a support structure or enclosure. The flexible circuit may be comprised of simple interconnects or may contain additional electrical elements such as resistors, capacitors, inductors, transistors or integrated circuits.

The invention may be embodied in other specific forms without departing from the spirit or essential characteristics thereof. The forgoing embodiments are therefore to be considered in all respects illustrative, rather than limiting of the invention.

What is claimed is:

1. A display assembly comprising:

an array of MEMS light modulators formed on a first substrate, each of the MEMS light modulators including a shutter that moves in a plane substantially parallel to the first substrate;

a second substrate separated from the first substrate by a gap;

an array of spacers arranged between the first and second substrates, the number of spacers being proportional to the number of MEMS light modulators;

a hydrophobic liquid disposed between the first and second substrates substantially surrounding a movable portion of each MEMS light modulator, the movable portion including an actuator having a first flexible electrode and a second flexible electrode; and

a moisture resistant polymer seal surrounding the array of MEMS light modulators to contain the hydrophobic liquid between the two substrates, the polymer seal including a polymer that serves to adhere the first substrate to the second substrate.

2. The display assembly of claim 1, wherein the hydrophobic liquid comprises a lubricant.

3. The display assembly of claim 1, comprising a reflective aperture layer disposed on one of the first and second substrates.

4. The display assembly of claim 3, wherein the hydrophobic liquid has a first index of refraction and the substrate on which the reflective aperture layer is disposed has a second index of refraction, and wherein the first index of refraction is greater than or substantially equal to that of the second index of refraction.

5. The display assembly of claim 1, wherein the hydrophobic liquid is non-conductive.

6. The display assembly of claim 1, wherein the hydrophobic liquid has a dielectric constant greater than 2.0.

7. The display assembly of claim 1, wherein the hydrophobic liquid wets a surface of the MEMS modulators in the array of MEMS light modulators.

8. The display assembly of claim 7, wherein each of the MEMS light modulators includes a front side and a rear side, and wherein the hydrophobic liquid wets both the front and rear sides of the MEMS light modulators.

9. The display assembly of claim 1, wherein each of the MEMS light modulators includes a component that is controllably moved through the hydrophobic liquid.

10. The display assembly of claim 1, wherein the hydrophobic liquid is a single hydrophobic liquid.

11. The display assembly of claim 1, wherein the polymer seal is an epoxy.

12. The display assembly of claim 1, wherein each spacer of the array of spacers is arranged within or adjacent to a pixel of the display assembly.

13. The display assembly of claim 1, wherein each spacer of the array is arranged to maintain a substantially uniform pressure on the hydrophobic liquid.

14. The display assembly of claim 1, wherein each spacer of the array of spacers is associated with one or more MEMS light modulators.

15. The display assembly of claim 1, wherein each spacer of the array of spacers is associated with a group of two or more MEMS light modulators.

16. The display assembly of claim 1, wherein each spacer of the array of spacers is associated with a group of sixteen or more MEMS light modulators.

17. The display assembly of claim 1, wherein each MEMS light modulator is associated with one or more spacers of the array of spacers.

18. The display assembly of claim 1, wherein the density of the spacers of the array of spacers is arranged to maintain the second substrate at about a constant distance away from each of the MEMS light modulators of the array of MEMS light modulators.

19. The display assembly of claim 1, wherein the moisture resistant polymer seal is located within the gap.

20. The display assembly of claim 1, wherein the moisture resistant polymer seal adheres to a surface of the first substrate facing the gap and to a surface of the second substrate facing the gap.

21. The display assembly of claim 1, wherein the first flexible electrode includes a support beam connected to the shutter.

22. The display assembly of claim 1, wherein each spacer includes a first portion and a second portion, the first portion including a heat reflowable material.

23. The display assembly of claim 22, wherein the material functions as an adhesive to bond the first portion with the second portion.

24. The display assembly of claim 22, wherein the first portion is formed on the first substrate and the second portion is formed on the second substrate.

25. The display assembly of claim 22, wherein the material includes a metal alloy.

26. The display assembly of claim 25, wherein the metal alloy includes at least one of Pb—Sn alloys, Pb—In alloys, Tl—Sn alloys, In—Cu—Sn alloys, Au—Sn alloys, and Bi—Sn alloys.

27. The display assembly of claim 22, wherein the material includes one of substantially pure In, Sn, Ga, and Bi.

28. The display assembly of claim 22, wherein the material is non-metallic.

29. The display assembly of claim 28, wherein the material includes glass.

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**30.** The display assembly of claim **28**, wherein the material includes at least one of barium-silicate, a lead-silicate glass, and a thermoplastic polymer.

**31.** The display assembly of claim **30**, wherein the thermoplastic polymer includes at least one of polyethylene, polystyrene, polypropylene, and natural or synthetic waxes.

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